EMPLOYING A DATA-DRIVEN APPROACH TO PROCESS-BASED MODELLING IN DELFT3D-FM: A HYBRID MODEL FOR SIMULATING SHOREFACE NOURISHMENT EVOLUTION

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Deltares
Enabling Delta Life

TU Delft

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ABSTRACT

In recent decades, a growing number of shoreface nourishments have been carried out along the Dutch coast to mitigate coastal erosion. Designing shoreface nourishments requires a comprehensive understanding of their complex morphological evolution to develop optimal solutions. However, accurately predicting this evolution in Delft3D-FM has proven challenging. Excessive flattening of nourishments in morphological process-based models leads to an inaccurate representation of the cross-shore profile, and the implications of this inaccuracy on longshore predictions remain unclear.

To address this issue, the framework of a hybrid model has been developed that seamlessly integrates a data-driven component into the process-based numerical model Delft3D-FM through Basic Model Interface. Contrary to previous study efforts, the focus is not on improving the representation of physical processes, but on incorporating a data-driven component into Delft3D-FM to more accurately represent observed behavior in cross-shore modeling. The presented modelling framework facilitates the prevention of excessive flattening of shoreface nourishments in Delft3D-FM by enabling user-defined manipulation of bed level changes during simulation.

The hybrid model is then applied to reproduce a shoreface nourishment at the coast of Ter Heijde for two main objectives: (1) to demonstrate the proof-of-concept of a hybrid model approach and (2) to examine how inaccuracies in cross-shore modelling affect longshore predictions, thereby highlighting the added value of a hybrid model approach. The latter is achieved by comparing the hybrid model with the standard, standalone Delft3D-FM model.

The results demonstrate the proof-of-concept of the hybrid model. Unlike the standard model, which showed excessive flattening of the nourishment, the hybrid model maintained its nourishment shape and followed observed cross-shore evolution over three months of morphological modelling.

We found that a hybrid model approach has the potential to more accurately represent the nourishment's lee effect, which plays a crucial role in the morphological response to a shoreface nourishment. By preventing excessive nourishment flattening, larger waves break earlier and/or more frequently in the hybrid model, causing a calmer wave climate in the lee of the nourishment compared to the standard model. This increased wave sheltering reduces the flow velocity in the lee which causes sediment supplied supplied by longshore currents to settle at a higher rate compared to the standard model, leading to increased sedimentation in the nourishment's lee.

As a result of the enhanced representation of the lee effect, the alongshore redistribution of sediment differs between the hybrid model and the standard model. After three months of morphological modeling, differences of 10-25% between the models attributed to the nourishment sediment are observed in the lee of the nourishment. Additionally, the hybrid model shows a trend of increasing divergence from the standard model over time, by maintaining a more pronounced lee effect that diminishes in the standard model. This indicates a sustained added value of the hybrid model over time.

These findings indicate that inaccuracies in cross-shore modeling have the potential to significantly impact longshore predictions over time, and that accurate cross-shore modelling leading to a more accurate representation of the lee effect should not be ignored when assessing longshore morphological changes in the context of shoreface nourishments.

This thesis represents a contribution towards a data-integrated approach in process-based modelling of the complex evolution of shoreface nourishments, highlighting the potential added value of such an approach. Therefore, we anticipate this thesis to be a starting point for more sophisticated ways to incorporate accurate cross-shore evolution by means of a hybrid model approach in the context of shoreface nourishments.

ACKNOWLEDGEMENTS

With this thesis, my time as a Hydraulic Engineering student at the faculty of Civil Engineering and Geosciences at TU Delft comes to an end. This report is the result of my research performed at Deltares in collaboration with TU Delft.

I would like to express my gratitude towards my supervisors: Dr. Arjen Luijendijk from Deltares, and Dr. Matthieu de Schipper and Dr. Joep Storms from the TU Delft. Writing this thesis has been an enlightening and invaluable learning experience, which has had its ups and downs, and I am thankful for the guidance you have provided. I hope my work has made a contribution towards unravelling shoreface nourishment modelling.

Arjen, I am grateful to have had you as my daily supervisor and mentor during my first steps into the field of coastal engineering. Your approachable character, expertise in this field, and eye for detail have helped me a lot. Matthieu, thank you for your feedback during our meetings. Your enthusiasm in unravelling the longstanding challenge of modelling shoreface nourishment evolution has motivated me throughout my thesis. To Joep, thank you for insightful feedback and reminder to take this research step by step. Furthermore, I would like to thank Bart van Westen for his guidance in understanding the CoCoNut model.

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To my parents and brother, a special thank you for the unconditional support I received during my time as a student. This journey has had its setbacks and breakthroughs, and I deeply appreciate your presence every step of the way.

Tom Bremer
Rotterdam, July 2024

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1 INTRODUCTION

1.1 BACKGROUND

Natural processes and human activities drive the structural erosion of the Dutch coastline. The sandy Dutch coast is a crucial area for flood protection and represents a unique domain of ecosystems, human habitation and economic opportunities (Stive et al., 1991; Turner et al., 1996).

The low-lying The Netherlands is prone to flooding as 60% of the surface would regularly flood without protective measures, posing a threat to nine million people (Rijkswaterstaat, 2015). Consequently, in 1990, the Dutch government decided to implement the 'Dynamic Preservation' policy, aimed at preventing any further inland retreat of the coastline at all costs by preserving the coastline with 'soft measures' using sand to mitigate potential erosion (Van Meulen et al., 2014).

To achieve this goal, the coastline is maintained by sand nourishments, making the Dutch coastline one of the most extensively nourished coastlines globally (Brand et al., 2021; De Ruig & Hillen, 1997). In the Netherlands, the most prevalent types of nourishments are beach and shoreface nourishments. Both are equally effective, but shoreface nourishments are generally more cost-effective and less disruptive to beach recreational activities. Therefore, a nourishment is nowadays performed underwater when possible and on the beach only when it is necessary, in line with the guideline: '*if possible nourish on the shoreface, if necessary nourish on the beach*' (Rijkswaterstaat, 2015).

Since the implementation of the Dutch Dynamic Preservation policy in 1990, the total nourishment volume increased significantly, with a noticeable trend towards shoreface nourishments over other nourishment types, as depicted in Figure 1.

Shoreface nourishments are typically placed just outside or just inside the outer breaker bar (Huisman et al., 2019). The main impact of a shoreface nourishment is to protect the beach by acting as a lee mechanism, modifying surf zone processes by forcing wave to break earlier and/or more frequently (Van Duin et al., 2004). This reduces the amount of wave energy that hits the beach, providing a sheltering effect that result in a non-eroding or accretive beach (Larsen et al., 2021).

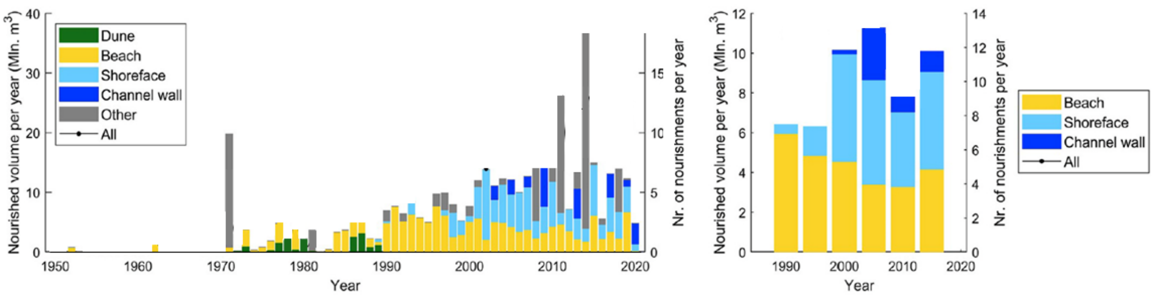


Figure 1: Overview of the annual nourishment volumes (in million cubic meters) categorized by the type of nourishment. Since 1990, with the implementation of the Dutch Dynamic Preservation policy, there has been a significant increase in total nourishment volume, with a noticeable trend towards shoreface nourishments over other types.

1.1.1 *Delft3D Flexible Mesh*

Delft3D Flexible Mesh (Delft3D-FM) (Deltares, 2023) is a process-based numerical model that can be used to help design shoreface nourishments and to assess their development. The model consists of several modules to compute amongst other the flow (FLOW-module), wave transformation (WAVE-module) and morphology (MOR-module, included in FLOW-module) in coastal waters. A more detailed description of Delft3D can be found in Appendix A.

While Delft3D is a leading, state-art-of-the-art numerical model, with a wide range of use cases, simulating shoreface nourishment evolution in Delft3D-FM poses significant challenges and remains an ongoing topic of research. Given the complexity of coastal processes, efforts to understand and predict the cross-shore evolution of shoreface nourishment are therefore grounded on coastal experience and expertise.

1.2 PROBLEM DESCRIPTION

Shoreface nourishments are widely used to safeguard the erosive Dutch coastline. However, accurately predicting the morphological evolution of shoreface nourishments in Delft3D-FM has proven challenging. The evolution of shoreface nourishment is strongly affected by three-dimensional (3D) processes that are currently not, or at least not accurately, incorporated in Delft3D-FM as the balance between offshore and onshore-directed cross-shore sediment transport is not accurately solved. As a result, the prediction of shoreface nourishment evolution, largely governed by the delicate balance of wave asymmetry and wave skewness related onshore transport and undertow related off-shore transport, cannot be modelled accurately in the process-based Delft3D-FM.

Several hindcast studies have been performed to study the performance of Delft3D in modelling shoreface nourishments along the Dutch coast. These studies were focused on two locations of shoreface nourishments, being Egmond aan Zee (Giardino et al., 2010; Van Duin et al., 2004) and Terschelling (Grunnet et al., 2004).

The key issue that is identified in these studies is the artificial flattening of the nourishment, leading to inaccurate and unreliable representation of the cross-shore profile. Grunnet et al. (2004) states that while bulk volumes integrated over large spatial scales are reasonably well predicted by the model, smaller-scale predictions of bed level evolution are poor due to the flattening of the cross-shore profile. Similarly, excessive flattening was observed in the study of Van Duin et al. (2004), see Figure 2. The model falls short in representing the cross-shore profile: excessive flattening of the nourishment is observed, while the model also failed to realize the separation of the nourishment from the outer bank. The intended effects of a shoreface nourishment related to the well-known lee and feeder effects, are only replicated over large spatial scales in the order of the alongshore length of the nourishment. Since the lee and feeder effects primarily result from the nourishment acting as a submerged breakwater, facilitating wave breaking and sheltering in its lee, excessive flattening as modelled within Delft3D-FM may lead to a rapid loss of this crucial function as modelled within Delft3D-FM.

To date, it is unclear to what extent the inaccurate representation of cross-shore processes, resulting in excessive flattening of the nourishment, affect the accuracy of predicting longshore morphological changes in Delft3D-FM.

For the evaluation of shoreface nourishments, there has often been a tendency to completely separate the longshore and cross-shore effects (Dean, 2002). According to Dean (2002), this is done both because the cross-shore developments are often seen to occur over much shorter timescales than those in longshore direction, and, perhaps more importantly, for practical reasons. Numerical models that work well for predicting longshore sediment transport are still not very accurate for predicting cross-shore sediment transport, and even state-of-the art numerical models struggle to accurately model cross-shore processes.

Given that morphological changes from a shoreface nourishment primarily result from its feeder and lee effect acting predominantly in cross-shore direction, significant inaccuracies in the cross-shore representation may impact the predictions of longshore morphological changes as well.

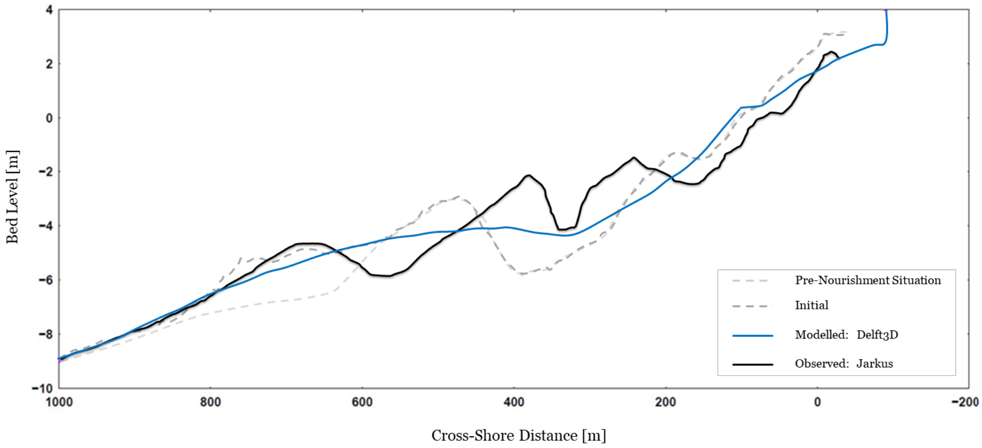


Figure 2: Excessive flattening of the cross-shore profile as modelled in Delft3D hindcast study conducted by Van Duin et al. (2004)

1.3 RESEARCH OBJECTIVES

The primary objective of this thesis is make a contribution towards incorporating more accurate cross-shore evolution in shoreface nourishment modelling, and study the added value of such an approach.

In the previous section, case studies in Egmond aan Zee and Terschelling highlighted the limitations of Delft3D in representing the cross-shore evolution of shoreface nourishments. The key issue identified is the artificial flattening of nourishment and the sandbars, leading to an overly smoothed cross-shore profile. Consequently, this results in unrealistic predictions for the initial years following a shoreface nourishment.

Prior efforts (e.g. Giardino et al. (2010), Grunnet et al. (2004), and Van Duin et al. (2004)) to improve Delft3D's cross-shore representation focused on adjusting model parameters to better represent the underlying physical processes involved, such as modifications to the calculation of the bed shear stress, the numerical scheme for computing sediment transport, and implementing a wave breaker delay. Although small improvements were made, the excessive flattened cross-shore profile continued to be a critical issue.

1.3.1 *A hybrid model*

As a result, this thesis's central focus is to improve predictions of cross-shore profile development. In this report, a new approach to achieve this is proposed, and contrary to previous study efforts, the focus is not on improving the representation of the physical processes involved, but on incorporating a data-driven component to the process-based Delft3D-FM model to more accurately represent observed behavior in the modeling of the cross-section. Therefore, this thesis can be seen as a pioneering study.

The aim is to integrate a data-driven component in the process-based numerical model Delft3D-FM. This approach keeps the process-based strengths while enriching it with a data-driven component to monitor the nourishment on excessive flattening, aiming for a more accurate representation of the cross-shore evolution of shoreface nourishments.

Subsequently, the impact of this approach on the model's ability to predict longshore morphological changes is studied, with the aim to get a better understanding of the implications of inaccurate cross-shore modelling on longshore predictions.

Two research objectives are defined:

1. Contributing to the development of a hybrid model that integrates a data-driven component into the process-based numerical model Delft3D-FM to more accurately capture the cross-shore evolution of the nourishment;

2. Examining the implications of cross-shore inaccuracies (i.e. excessive flattening) on longshore predictions, thereby contributing to a better understanding of the potential added value of a hybrid model incorporating realistic cross-shore modeling.

1.3.2 *Relevance*

For the design and approval of a shoreface nourishment, accurate and reliable information on anticipated morphological changes is essential to arrive at optimal solution, both in the short term as in the longterm. Without this information, the design is grounded on coastal experience and expertise, making the design highly empirical. This approach can lead to unforeseen and potentially unfavourable behavior. For example, nourishment areas may experience rapid sand erosion, potentially leading to unplanned maintenance of nourishments earlier than expected.

To this moment, no numerical model can provide detailed information on the cross-shore profile development in the initial years following a shoreface nourishment. This thesis aims to contribute to the development of a hybrid model that combines the process-based numerical model Delft3D-FM with a data-driven component. The goal is to more accurately represent cross-shore evolution, thereby improving the overall assessment of the morphological impact of a shoreface nourishment, and to evaluate the added value of this approach.

1.3.3 *Research Questions*

In order to address the issues of inaccurately representing cross-shore evolution in the context of shoreface nourishments, the following main research question and its sub-questions have been formulated:

Main Research Question

To what extent can a hybrid model, integrating a data-driven component into the Delft3D-FM, enhance its accuracy in modelling the morphological impact of a shoreface nourishment?

In order to answer the main research question, the following set of sub-questions are developed that provide a more detailed and specific focus for the study:

1. *To what extent do present-day Delft3D-FM models show excessively flattening of the cross-shore profile, and is there a dependency on forcing conditions?*

2. *Can the integration of a data-driven component into the process-based Delft3D-FM trough Basic Model Interface mitigate excessive artificial flattening of shoreface nourishments?*

3. *What are the implications of inaccurate cross-shore modelling on longshore morphological predictions in the context of shoreface nourishments?*

By answering these questions, this study aims to make a contribution to achieve more accurate modelling of the evolution and morphological impact of shoreface nourishments.

1.4 OUTLINE

The outline is shown in Figure 3. This thesis contains seven chapters. Chapter 2 and Chapter 3 address the Problem Analysis, which studies the behavior of shoreface nourishments in Chapter 2, and evaluates the performance of present-day process-based modelling of shoreface nourishments in Delft3D-FM in Chapter 3.

The theoretical background gathered in the Problem Analysis (Chapter 2 + Chapter 3) is then used to build the research methodology, which introduces the framework of the integration of a data-driven component in Delft3D-FM and elaborates on the methodology for demonstrating its Proof-of-Concept by applying the hybrid model to a case study of a shoreface nourishment in Ter Heijde.

Chapter 5 presents the findings, demonstrating the Proof-of-Concept of the hybrid model and evaluating the difference in modelled morphological impact between the hybrid model and standard model.

Chapter 6 discusses the results, and investigates the added value of a data-driven approach to Delft3D-FM, which is then followed by the conclusions and recommendations in Chapter 7.

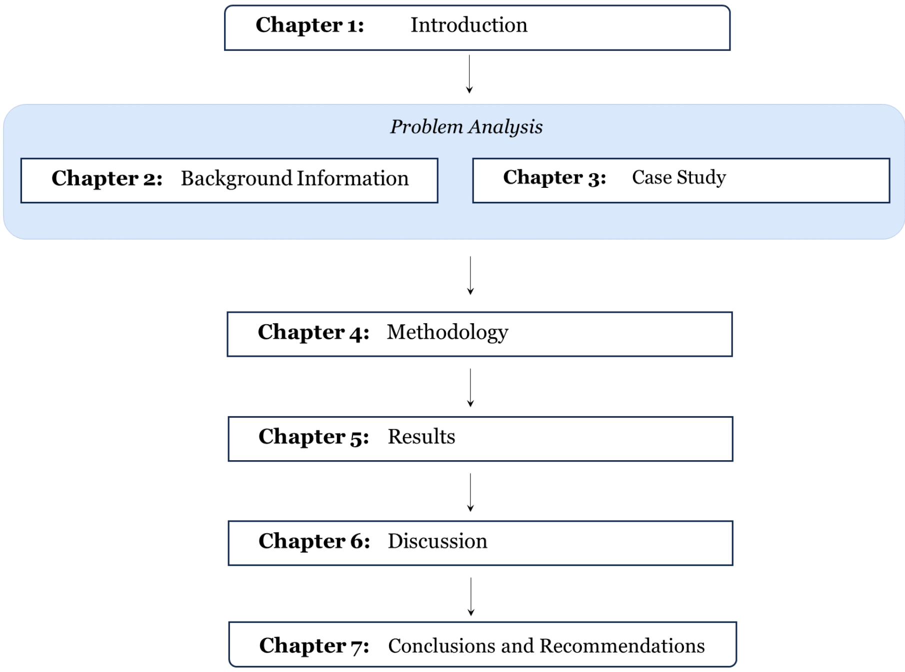


Figure 3: Thesis Outline

BACKGROUND INFORMATION 2

This chapter provides the theoretical background for this thesis. It explores the processes that govern the overall morphological behavior and timeline of a shoreface nourishment. Furthermore, it evaluates the performance and limitations of using Delft3D-FM to analyse the design and evolution of shoreface nourishments.

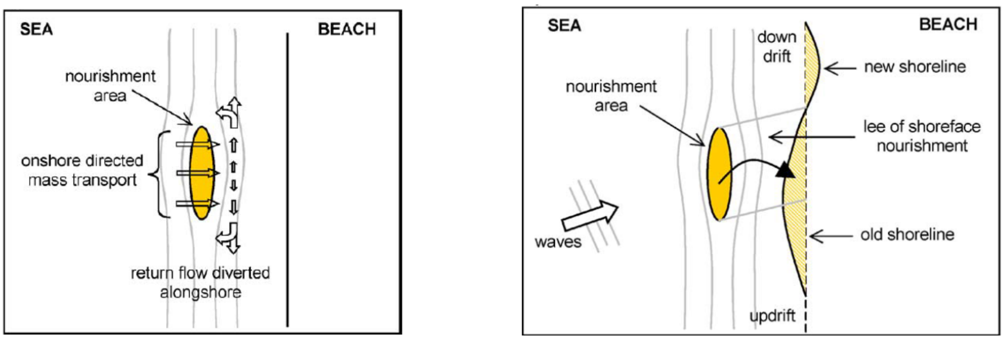
2.1 MORPHOLOGICAL BEHAVIOR OF SHOREFACE NOURISHMENTS

Implementing shoreface nourishments is a common strategy used in the Netherlands to mitigate structural erosion. Typically, they are positioned as close to the shore as possible, at a depth of MSL -5 m or deeper. In the presence of a sandbar system, the nourishment is placed against the seaward side of the outer bar. Shoreface nourishments typically extend for several kilometers along the shoreline and have a width of approximately 250 meters in cross-shore direction (Spanhoff, 2007).

The morphological effect of a shoreface nourishment can be compared to that of a submerged breakwater. The two most important effects of a shoreface nourishment are the 'lee effect' and the 'feeder effect' (Li et al., 2021; Van Duin et al., 2004):

THE FEEDER EFFECT primarily operates in the cross-shore direction, and describes how a shoreface nourishment acts as a 'sediment reservoir,' supplying additional sediment to the beach-dune system. When large waves break on the seaward side of the shoreface nourishment, the remaining waves that shoal generate onshore transport due to asymmetry, thereby increasing sediment transport towards the shore, see Figure 4a.

THE LEE EFFECT, describes how large waves break at the shoreface nourishment causing a calmer wave climate behind the shoreface nourishment. This reduces the longshore currents and hence the transport capacity in the lee of the nourishment, resulting in updrift sedimentation and downdrift erosion, see Figure 4b.



((a)) The feeder effect ((b)) The lee effect

Figure 4: Effects expected to occur as a consequence of a shoreface nourishment: (a) the feeder effect causes onshore sediment transport due to wave asymmetry. (b) The lee effect provides a wave shadow zone, reducing longshore transport and thereby promoting sedimentation in the lee of the nourishment. Source: Van Duin et al. (2002a).

Over time, the lee and feeder effect of a shoreface nourishment diminishes as its volume decreases. Estimating the lifespan of shoreface nourishments is challenging due to their complex behavior, but they typically have an impact on the shoreline ranging from 4 to 10 years (Witteveen+Bos, 2006).

2.2 THREE-DIMENSIONAL DYNAMICS IN THE NEARSHORE ZONE

The interplay of three-dimensional hydrodynamic and morphodynamic processes, and the balance between its resulting offshore- and onshore directed sediment transport, play a crucial role in the morphological evolution of shoreface nourishments (Walstra, 2016). The nearshore zone is a dynamic zone where waves break and dissipate their energy as they interact with the seabed (Gallop et al., 2021). When considering sediment transport in the coastal zone, a distinction is made between cross-shore and longshore sediment transport. Cross-shore transport occurs due to a combined effect of the orbital velocities caused by wave asymmetry and undertow caused by breaking waves in the surfzone (Henrotte, 2008). Longshore transport, on the other hand, is caused by the longshore current that is driven by radiation stress of waves approaching under an angle (Bosboom & Stive, 2023).

Surfzone currents are generated by wave action in the breakerzone and is mostly driven by gradients in radiation stress that are produced by wave breaking. The velocity field in the surfzone is complex as the cross-shore velocity profile exhibits strong vertical variation (Henrotte, 2008), as can be seen in Figure 5. Breaking waves induce radiation stress and water level gradients due to wave set-up. Consequently, the water in the top layer is directed onshore, and forces the water back in offshore direction in the bottom layers as a secondary return current, i.e. undertow (Gallop et al., 2021). These cross-shore currents, though usually rather weak compared to the longshore currents, has significant effects on cross-shore sediment transports and bed dynamics (Huisman, 2019).

The combined effect of 3D cross-shore and longshore currents in the surfzone is illustrated in Figure 5, in which significant variation in the vertical (z-direction) can be observed. However, in Delft3D-FM, this balance between offshore and onshore directed transport is not adequately accounted for as the depth-averaged computations in Delft3D-FM fail to reproduce these 3D effects in the surfzone. As a result, the evolution of a shoreface nourishment, largely governed by the interplay of onshore directed processes as wave asymmetry and wave skewness, and offshore directed processes as undertow, remains a challenge in Delft3D-FM, leading to an excessively flattened cross-shore profile.

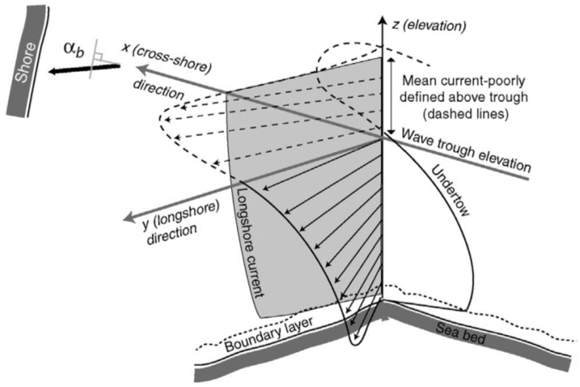


Figure 5: Three-dimensional velocity field in the surfzone (from Gallop et al. (2021))

2.3 NUMERICAL MODELLING OF SHOREFACE NOURISHMENTS IN DELFT3D-FM

Delft3D Flexible Mesh, is a numerical model designed to employ process-based simulations for detailed insights into hydrodynamics, sediment transport and morphological processes in coastal environments. Delft3D-FM can be used to help design shoreface nourishments and to assess their development, but often lacks the desired level of accuracy (Tonnon et al., 2018; Trouw et al., 2012a; Walstra et al., 2004). While Delft3D-FM is a leading, state-of-the-art numerical model, with a wide range of usecases, simulating shoreface nourishments remains an ongoing topic of research.

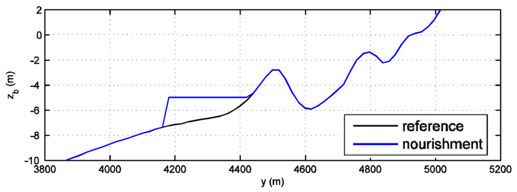
2.3.1 *Modelling challenges in Delft3D-FM*

Modelling the behaviour of shoreface nourishments poses significant challenges. Cross-shore transport, as highlighted by Huisman et al. (2019), is the primary contributor to nourishment erosion, responsible for 60-85% of losses. This process is strongly affected by three-dimensional (3D) effects, as discussed in Section 2.2, that are currently not, or at least not accurately, accounted for in Delft3D-FM (Franz et al., 2017; Kristensen et al., 2011; Seenath, 2022; Walstra et al., 2004).

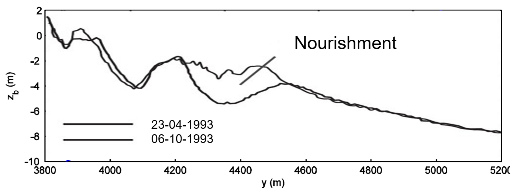
Several hindcast studies (Giardino et al., 2010; Grunnet et al., 2004; Van Duin et al., 2004) have been performed to study the performance of Delft3D-FM's predecessor, Delft3D (Lesser et al., 2004), in modelling shoreface nourishments along the Dutch coast. The key issue that is identified in these studies is the excessive flattening, leading to an inaccurate and unreliable representation of the cross-shore profile, as summarized in Figure 6.

The hindcast studies (Giardino et al., 2010; Grunnet et al., 2004; Van Duin et al., 2002b) were focused on two shoreface nourishments along the Dutch coast, being Egmond aan Zee (Giardino et al., 2010; Van Duin et al., 2004) and Terschelling (Grunnet et al., 2004). At Egmond aan Zee, a shoreface nourishment was applied in the summer of 1999, and spanned approximately 2 kilometers long and 200-m wide. The coastal profile is characterized by a three-bar system, and the shoreface nourishment was applied at the seaward side of the outer bar (Figure 6a). Van Duin et al. (2004) assessed the performance of Delf3D in hindcasting the shoreface nourishment at this location. Model results show that Delft3D falls short in representing the cross-shore profile: excessive flattening of the nourishment is observed, while the model also failed to realize the separation of the nourishment from the outer bank, see Figure 6c. Furthermore, a much smaller onshore movement of the modelled profile is observed compared to the measured profile at May 2000.

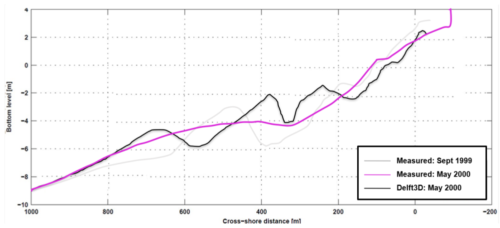
In the study of Giardino et al. (2010), the same outcome is observed, as it concludes that the nourishment and breaker bars are excessively flattened during the simulations.



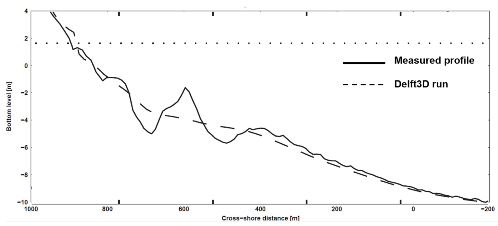
((a)) Location of the shoreface nourishment at Egmond aan Zee.



((b)) Location of the shoreface nourishment at Terschelling.



((c)) Findings of Van Duin (2004) at Egmond aan Zee.



((d)) Findings of Grunnet et al. (2004) at Terschelling.

Figure 6: Delft3D hincast studies overview at locations Egmond aan Zee (subfigures (a), (b) and (c)) and Terschelling (subfigures (d) and (e)).

Another location at which Delft3D is tested, is Terschelling (Figure 6c). In 1993, the NOURTEC shoreface nourishment was applied, which filled the trough between the outer and middle bar with a total of two million cubic meters of sand (Kroon et al., 1994). Grunnet et al. (2004) employed Delft3D for hindcasting this nourishment. The study focused on a five month period following the nourishment, during which significant morphological changes occurred. The study concludes that Delft3D has the potential to simulate shoreface nourishments. However, it highlights several key issues that need to be addressed. Notably, the bars do not persist in the morphodynamic simulation; instead, they flatten, see Figure 6d, with particular emphasis on the middle bar. Despite experimenting with multiple parameter settings to reduce bar flattening, excessive bar flattening still occurred. Additionally, the model failed to replicate the vertical and horizontal growth of the middle bar resulting from observed onshore nourishment movement.

Overall, the modeling of cross-shore bed-level changes in Delft3D is deemed extremely inadequate, and the observed cross shore migration and bar development are not accurately reproduced; bars seem to disperse rather than migrate. The key issue identified is the excessive artificial flattening of the cross-shore profile, leading to an inaccurate and unreliable representation of the cross-shore profile.

2.3.2 *Causes of cross-shore profile flattening*

The main cause of excessive flattening of the cross-shore profile is attributed to Delft3D-FM's insufficient representation of three-dimensional (3D) effects in cross-shore direction as discussed in Section 2.2. Delft3D-FM fails to adequately incorporate and balance off-shore directed processes, such as wave asymmetry and wave skewness, with on-shore directed transport, specifically undertow. As a result, the evolution of shoreface nourishment, largely governed by the interplay of onshore- and offshore directed processes, remains a challenge in Delft3D-FM (Franz et al., 2017; Giardino et al., 2010; Walstra et al., 2008).

Table 1 summarizes the 3D cross-shore transport processes with regards to their implementation in Delft3D-FM. Based on Trouw et al. (2012b), the relevant cross-shore processes are ranked on relative importance in influencing shoreface nourishment behavior. Essential 3D cross-shore processes are not incorporated in the model, impacting its ability to accurately model the evolution of shoreface nourishment.

Process	**Relative Importance Shoreface Nourishments**	**Delft3D**
Undertow	4	No (hydrodynamics only)
Wave Asymmetry	4	No
Wave Skewness	4	Yes
Long Waves	4	No
Turbulence	3	No
Wave Roller	3	Limited
Gravity	3	Yes (correction of bed load transport)
Bed Forms	2	Yes
Boundary Layer Streaming	1	Yes
Settling Velocity	1	No
Stokes' Drift	1	No

Table 1: The implementation of cross-shore processes in Delft3D-FM and their relative importance (1: less important, 4: most important). Essential 3D cross-shore are not incorporated, leading to excessive flattening of the cross-shore profile.

2.4 BEHAVIORAL CHARACTERISTICS OF SHOREFACE NOURISHMENTS

This section outlines a timeline that is broadly applicable to shoreface nourishments along the Dutch coast, aiming to establish criteria for a data-driven approach to Delft3D-FM, which will be discussed later in this thesis.

2.4.1 *Timeline of a shoreface nourishment*

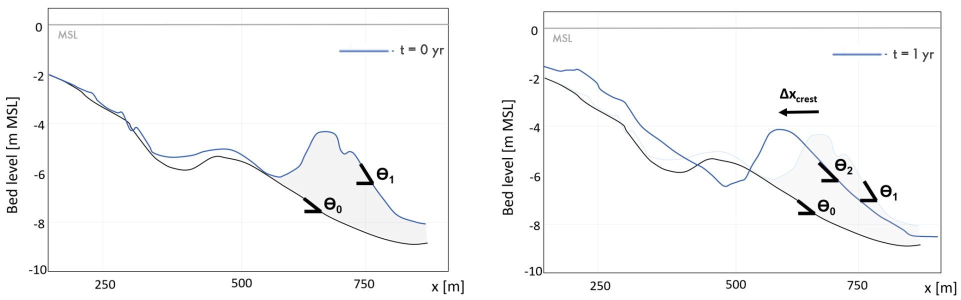
Figure 7 provides a timeline illustrating the evolution of a shoreface nourishment over time derived from observations of 19 shoreface nourishments as documented in Huisman et al. (2019). The timeline includes various steps from construction to the end of its lifetime. Each step is accompanied by observations regarding the changes in the nourishment's characteristics, such as its crest height, trough depth and slopes.

Figure 7a depicts the initial placement of the shoreface nourishment, shown as gray area. Typically, within one to two years, the nourishment crest reaches a depth of about MSL -4 to -5 m, positioned between x=400 and x=800 m from the shoreline, aligning with the highest bar amplitudes along the Holland coast. One year later, a landward shift (Δx) and an increase in crest height are noticeable, see Figure 7b

Furthermore, after construction, the seaward side of the nourishment erodes. As a result, the seaward facing slope of the nourishment has the tendency to become milder (from Θ_1 to Θ_2) and therefore more similar to the pre-construction profile slope (Θ_0), see Figure 7a and Figure 7b. Just after construction, the seaward facing side of the nourishment has an average profile slope of 1:50 with a standard deviation (SD) of 33 (for the first post-construction survey), and is therefore much steeper than the natural profile slope of 1:100 to 1:200. This relatively steep profile gradually becomes milder over time with an average slope of 1:80 for the considered nourishments after 3 years (with a SD of 48) (Huisman et al., 2019).

On the contrary, the landward facing slope of the nourishment became steeper in the first years due to an increase in crest height of the nourishment and the development of a trough at the landward side ($\Delta_{y,\mathrm{trough}}$) between MSL -4 m and -6.5 m, which can be seen in Figure 7c. The mean depth of the trough with respect to a long-term averaged profile is 0.5 to 2 m, which was within the bounds of the natural bar-migration cycle. When considering all the nourishments, the trough depth seemed to be related to regional characteristics rather than a geometry related property (e.g., the length or volume of the nourishment).

By approximately four to five years (Caljouw, 2000; Ruessink & Kroon, 1994), the onshore migration halts, and the natural offshore direction resumes, marking the end of the nourishment lifetime as it flattens and aligns closer to the natural profile (Figure 7e).



((a)) Initial placement of the shoreface nourishment, marked by the grey area.

((b)) Noticeable landward shift (Δx), increased crest height and milder seaward-facing slope.

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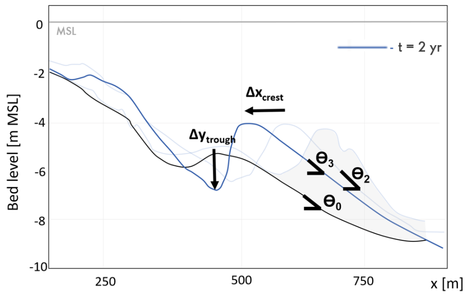
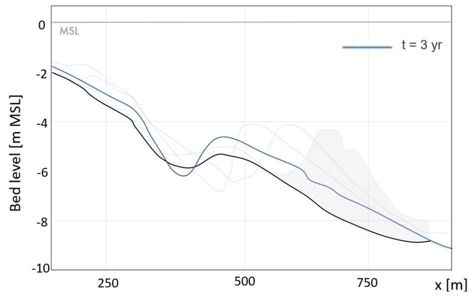
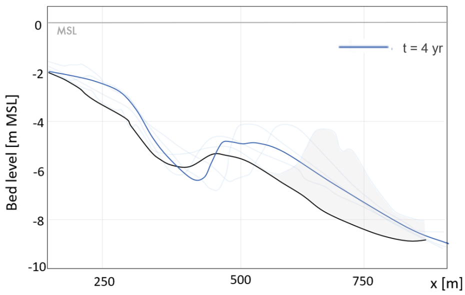


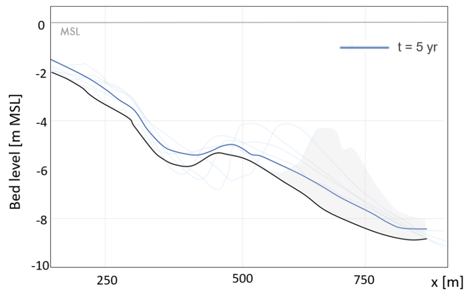
((d)) Formation of a trough and continued increase of crest height.



((e)) Landward shift and increase of crestheight slows down.



((f)) The onshore migration halts, and the natural bar offshore migration returns.



((g)) End of the nourishment's lifecycle. The nourishment has flatten out.

Figure 7: Broadly applicable timeline of a shoreface nourishment derived from 19 shoreface nourishments along the Dutch coast as documented in Huisman et al. (2019).

2.4.2 *Characteristics of shoreface nourishment evolution*

The previous section presented a timeline that is broadly applicable for the evolution of shoreface nourishments along the Dutch coast. Insight in this timeline is important for developing a data-corrected approach. Currently, the results of shoreface nourishments modelled in Delft3D deviate from this timeline as they show excessive flattening of the cross-shore profile. The following characteristics in the evolution of a shoreface nourishments are identified:

- Landward shift and crest height increase (i.e. not rapidly diffusing)
- Milder seaward facing slope
- Steeper landward facing slope and trough formation
- Resumption of natural bar cycle after four to five years

These characteristics should be incorporated into a data-corrected approach to Delft3D-FM and will guide the setup of the modeling system to ensure the observation of these aspects in its simulations.

2.5 DEVELOPMENTS OF MODELING TECHNIQUES IN DELFT3D-FM

The hindcast studies as discussed in Section 2.3 were conducted two decades ago with Delft3D, the predecessor of Delft3D-FM. This section reviews the evolution of Delft3D since those hindcast studies, highlighting the most important improvements to the model in light of modelling shoreface nourishments. Chapter 3 assesses whether or not these developments contribute to more accurate shoreface nourishment in present-days models compared to the hindcast studies. The two most relevant developments are:

- Model improvements
- Introduction of Delft3D Flexible Mesh
- Improvements in Forcing Conditions

2.5.1 *Model improvements*

Delft3D-FM is a continuously evolving model, undergoing frequent updates and developments to improve its accuracy. One significant advancement is the introduction of Delft3D Flexible Mesh Suite, the successor of Delft3D, which offers more flexibility in mesh generation and adaptation. This allows for better representation of complex bathymetries and varying resolutions in different areas of the model domain, which could be useful to more accurately resolve surfzone processes with a finer resolution, potentially adding to increased performance in modelling the important cross-shore evolution of shoreface nourishments.

2.5.2 *Improvements in the representation of forcing conditions*

There are notable differences in forcing conditions between the model setups used in hindcast studies (Giardino et al., 2010; Grunnet et al., 2004; Van Duin et al., 2004) and present-day models. The hindcast studies used wave schematization techniques, aiming to reduce the number of wave input conditions while still representing the prevailing wave climate. In contrast, present-day models typically use brute force (BF) techniques, or variations from the BF method. BF methods use real-time time series of forcing conditions (Luijendijk, 2019).

The wave schematization techniques used in the hindcast studies focus on reducing the number of wave input conditions resulting in a set of representative conditions to best reflect the prevailing wave climate (Luijendijk et al., 2019). For example, the hindcast study of Van Duin et al. (2004) used a set of schematized wave conditions in which the yearly average longshore transport (LST) is reproduced. For this purpose, the study computed the LST for the entire wave climate (+ 200 wave conditions), and then determined a set of 12 wave conditions that reproduced similar LST values to schematize the wave climate while reducing the input. This schematized wave climate is the used to forecast morphological changes.

In contrast to the above mentioned representative wave forcing conditions, the approach often used nowadays is Brute Force time serie simulations. This approach uses real-time time series of forcing conditions. Three variations of the BF technique are commonly used: Brute Force (BF), Brute Force-Filtered (BFF) and the Brute Force - Filtered Compressed (BFFC). The BFFC method not only filters the wave climate as in the BFF method based on wave height, but also compresses it using a morphological acceleration factor (morfac) to accelerate morphological changes.

According to Luijendijk et al. (2019), brute force techniques perform better in predicting cross-shore distribution of the deposited sand compared to wave schematization techniques in the Sand Engine modelling study. This is an interesting observation as modelling of shoreface nourishments largely relies on cross-shore transport, potentially suggesting that the degree of cross-shore flattening may be less severe in present-day models compared to hindcast studies.

Chapter 3 will examine whether or not conclusions of previous hindcast studies are still valid, despite two decades of developments and advancements of Delft3D-FM models.

3 CASE STUDY

This chapter assesses the performance of present-day process-based modelling of shoreface nourishments in Delft3D-FM by conducting a case study on the shoreface nourishment of 1997 at the coast of Ter Heijde. In Section 1.2, previous hindcast studies (Grunnet et al., 2004; Van Duin et al., 2004) highlighted the inaccurate and unreliable representation of cross-shore evolution of shoreface nourishments in Delft3D. The primary issue observed was the excessive flattening of the cross-shore profile.

The case study at Ter Heijde is conducted to assess the ongoing relevance of these previous hindcast studies in light of updates to Delft3D since the publication of these studies. With the continuous development and updates in Delft3D, including the introduction of Delft3D-FM and the capability to conduct brute force simulations, a step in time is taken from the hindcast studies to see if, and to what extent, present-day Delft3D-FM models still demonstrate unrealistic representation of cross-shore profiles, as concluded many years ago.

3.1 CASE STUDY: TER HEIJDE

The shoreface nourishment of 1997 in Ter Heijde is used as case study (see Figure 8). This nourishment was constructed in August of 1997 between Jarkus transects 9011315 to 9011485.

The coast at Ter Heijde is characterized by a relatively smooth cross-shore profile, featuring only one moderately sized sandbar (see Figure 9a). The absence of a complex sandbar system makes this coastal section suitable location for the assessment of the ongoing relevance of past studies.

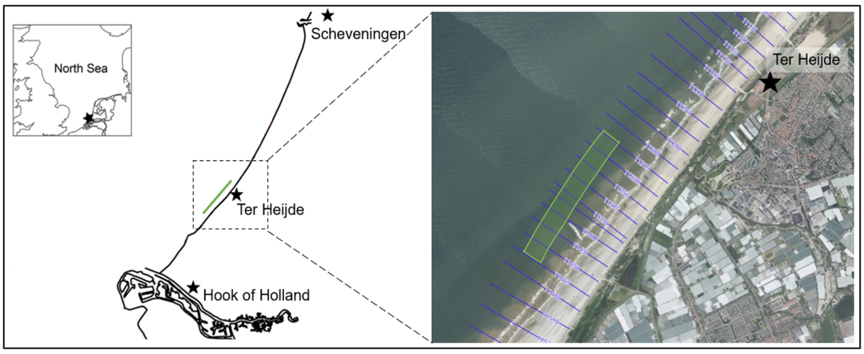


Figure 8: Location of the Ter Heijde '97 shoreface nourishment

3.1.1 *Design of the nourishment*

The shoreface nourishment spans 1700 meters in alongshore direction with a width of 300 meters, and is located at a depth -8 to -5 m MSL. The characteristics of the design are summarized in Table 2.

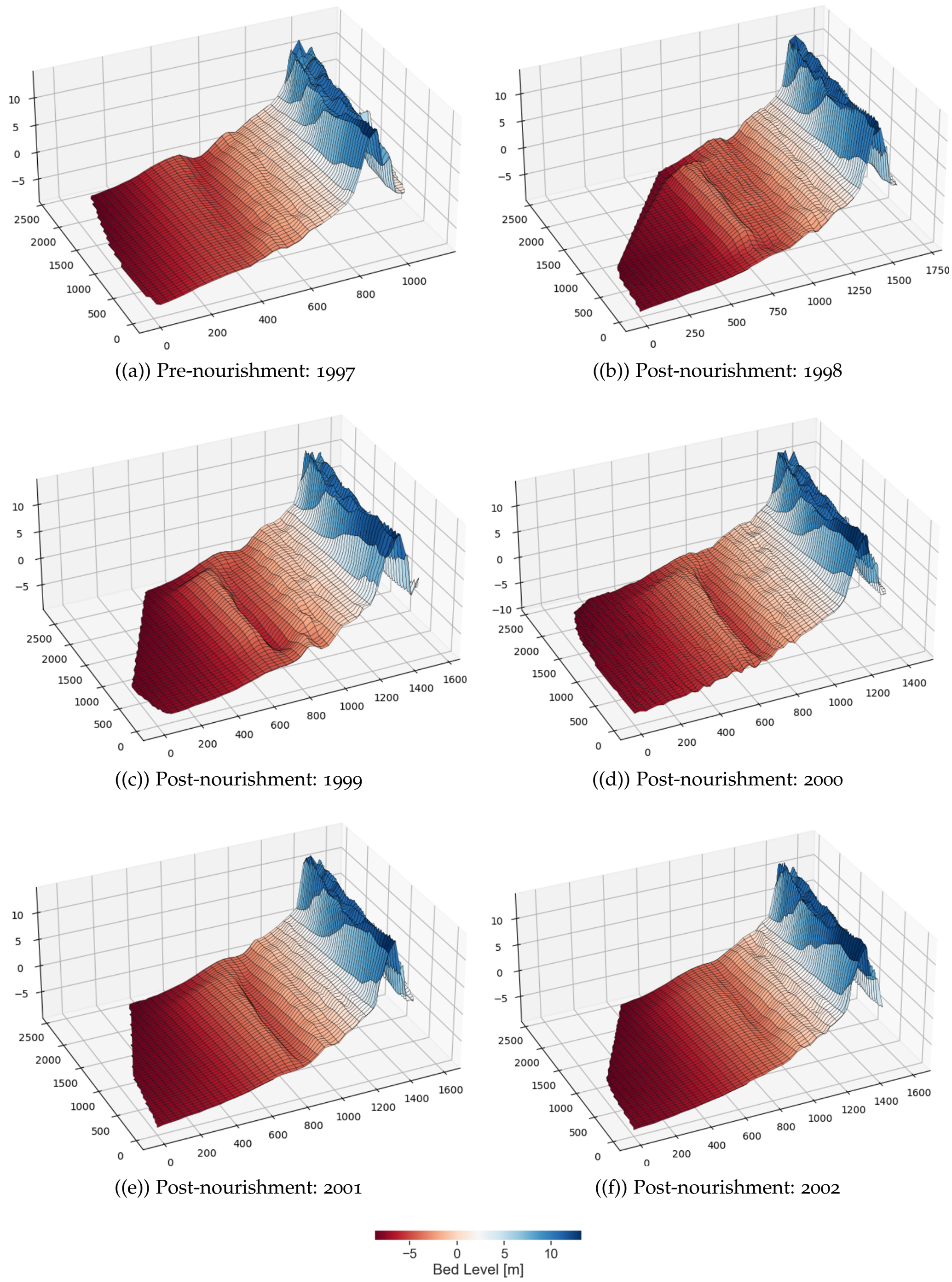
T_0	Coastal Section	Jarkus Transects	Volume [m^3]	Density [m^3/m]	LxW [km]	Depth [m MSL]
Aug-97	Delfland	9011315-9011485	882.605	517	1.7x0.3	-8 to -5

Table 2: Design of the shoreface nourishment at Ter Heijde

3.1.2 *Evolution of the Ter Heijde '97 shoreface nourishment*

Figure 9a shows a bird's eye view of the observed situation before the construction of the nourishment, and Figure 9b shortly after. The nourishment is constructed at the seaward side of the only sandbar present.

The observed evolution of the shoreface nourishment aligns with the timeline that was identified as broadly applicable to shoreface nourishments along the Dutch coast (Section 2.4), see Figure 9. After placement of the nourishment, the crest of the nourishment undergoes an increase in height and steepness, accompanied with the formation of a trough. Over time, the nourishment starts diffusing until the end of its lifecycle, approximately 4-5 years after construction.



((a)) Pre-nourishment: 1997 ((b)) Post-nourishment: 1998

((c)) Post-nourishment: 1999 ((d)) Post-nourishment: 2000

((e)) Post-nourishment: 2001 ((f)) Post-nourishment: 2002

Figure 9: Evolution of the Ter Heijde '97 nourishment over a five-year period. The crest undergoes an increase in height and steepness, together with the formation of a trough, while ultimately diffusing towards the end of its lifetime.

The Ter Heijde '97 nourishment evolution aligns with the four behavioral characteristics of the evolution of a shoreface nourishment that were identified in Section 2.4.2, being: (1) landward shift and crest height increase, or at least maintaining its crest height (i.e. not flattening out excessively as observed in hindcast studies), (2) milder seaward facing, (3) steeper landward facing slope and development of a trough and (4) the resumption of the natural bar cycle after four to five years.

A modelling study in Delft3D-FM is carried out to determine if these four characteristics can be observed in the evolution of the shoreface nourishment at Ter Heijde in present-day Delft3D-FM models, or excessive flattening of the cross-shore profile still occurs.

3.2 MODEL SET-UP

3.2.1 *Modelling approach*

The Delft3D-FM model used in this case study is an adapted version of the model by Luijendijk et al. (2017). This model was developed and validated to assess the evolution of the Sand Engine, four kilometers north of the shoreface nourishment at Ter Heijde.

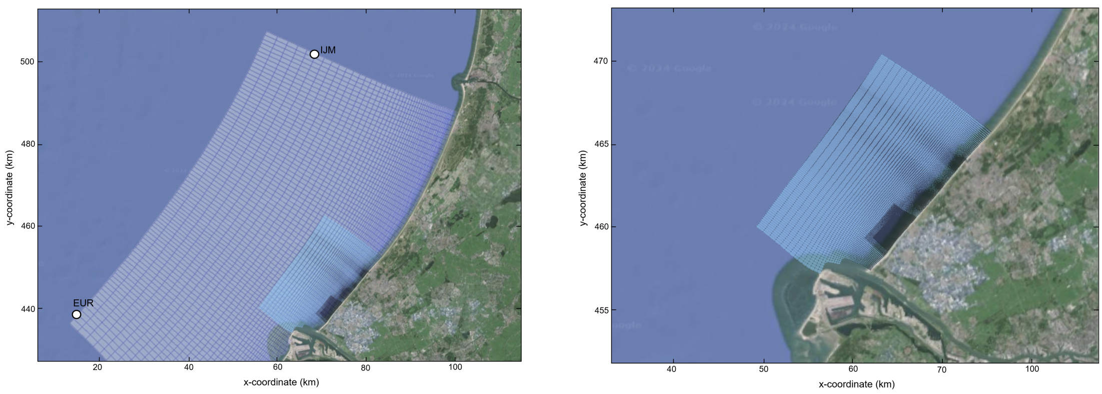
For this particular case study, the model is configured to conduct brute-force compressed morphodynamic simulations over the lifespan of shoreface nourishments (approximately 5 years). The computations are performed on Deltares' h6 Linux-cluster, utilizing four nodes with four cores each (totalling 16 cores).

The modeling approach aims to get a better understanding of the computed evolution in present-day Delft3D-FM models in the initial years following a shoreface nourishment. This includes assessing whether or not excessive flattening occurs in the model, and if so, to what extent. Furthermore, the redistribution of sediment in case of flattening will be assessed, aiming to identify aspects that require improvement in the data-driven approach to Delft3D-FM later on in this thesis.

3.2.2 *Model subdomains and grid layouts*

Figure 10 visualizes the model subdomains and grid layouts. The layouts are based on Luijendijk et al. (2017). For modelling of wave propagation in SWAN, two nested domains were applied as depicted in Figure 10a. Inside this larger grid, a finer grid with increased cross-shore resolution is applied.

Figure 10b shows the domain for the Delft3D-FM model. For this domain an unstructured grid is applied, covering an alongshore stretch of 20 km from Hook of Holland to Scheveningen. The original grid as used in Luijendijk et al. (2017) has been refined at the location of the shoreface nourishment at Ter Heijde to better capture the cross-shore evolution.



((a)) SWAN ((b)) Delft3D-FM

Figure 10: Layout of the computational domain. (a) shows the SWAN domain with two nested domains. (b) shows the Delft3D-FM domain, in which a refinement of the grid is applied at the location of the shoreface nourishment.

3.2.3 *Bathymetry*

The simulated bathymetry for the Ter Heijde '97 shoreface nourishment is derived from Vaklodingen and Jarkus measurements, see Figure 11. High-resolution bathymetry data from Vaklodingen is integrated with more recent Jarkus measurements from the nourishment area, as the Jarkus survey was conducted closer to the time of construction.

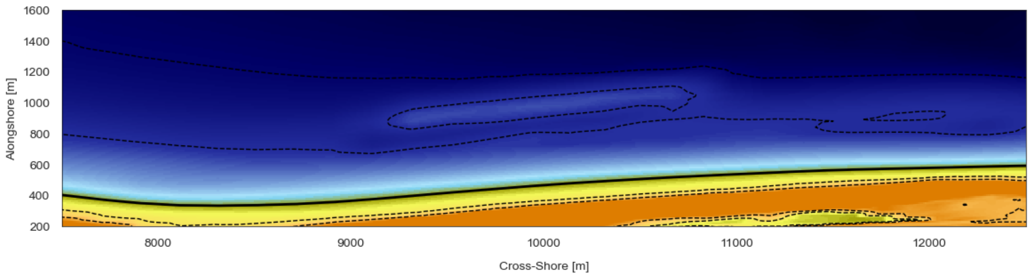


Figure 11: Simulated bathymetry for the Ter Heijde '97 shoreface nourishment with 5m contours and thick line represents the 0m line.

3.2.4 *Forcing conditions*

The model is driven by measured time series data from two off-shore platforms: Europlatform (EUR) and IJmuiden Munitiestortplaats (IJM). The wave characteristics of height, period and direction are measured here. The locations of the two off-shore platforms are shown in Figure 10a and measured timeseries are depicted in Figure 12.

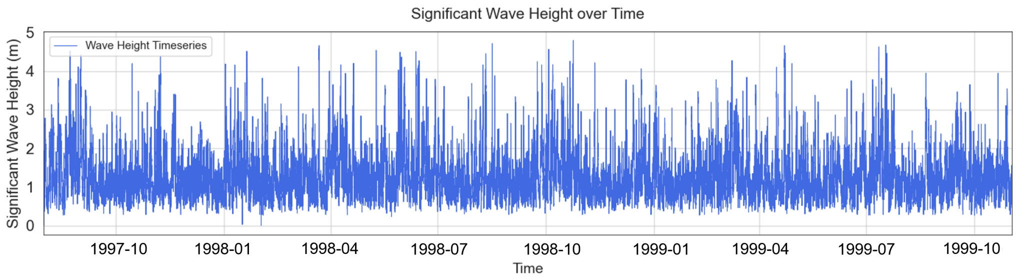


Figure 12: The wave height timeseries in the simulation period July 1997 until October 1999.

3.2.5 *Model settings*

Table 3 summarizes the most important model settings. The Delft3D FM model is set up to evaluate the evolution of shoreface nourishments through morphodynamic simulations. For these simulations, a morphodynamic acceleration factor (morfac) of 3 is used to speed up the simulations.

Module	**Symbol**	**Description**	**Value**	**Unit**
Hydrodynamics	V_H	Uniform horizontal eddy viscosity	1	m^2/s
	D_H	Uniform horizontal eddy viscosity	1	m^2/s
SWAN	Gammax	Wave breaking threshold in Delft3D-FM	0.7	-
Transport	D_{50}	Median grain size	0.00025	m
	Formulation	Sediment transport formulation	Van Rijn (2004)	-
Morphology	*morfac*	Morphodynamic Acceleration Factor	3	-

Table 3: Model settings for Delft3D-FM

3.3 MODEL RESULTS

After setting up the model, the model is ran for a 5-year simulation period under brute-force conditions. The model's ability to replicate Jarkus measurements is assessed by comparing the observed cross-shore profile with the modelled cross-shore profile, see Figure 13. Three characteristic transects are defined: 'Transect A' positioned at the left boundary of the nourishment, 'Transect B' at the center and 'Transect C' at the right boundary. For these transects, the pre-nourishment cross-shore profile, the initial post-nourishment profile, the observed Jarkus profile after one year, and the modeled Delft3D-FM cross-shore profile after one year are plotted as shown in Figure 13.

The observed cross-shore profile shows that the construction of the shoreface nourishment has led to both landward migration and increase of crest height, along with the formation of a trough. The model does not include these features, as the cross-shore profile is flattened out.

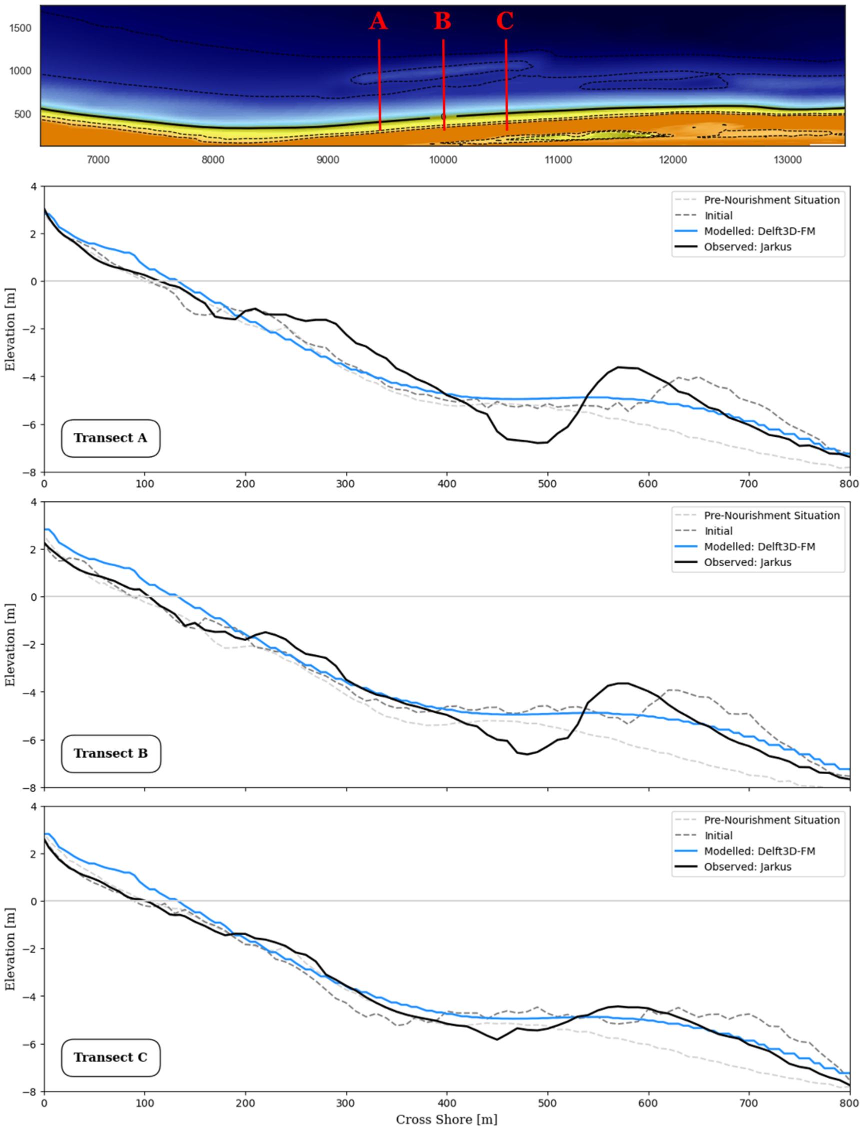


Figure 13: Comparison between observed and modeled cross-shore profiles. Observed cross-shore profile shows crest height increase, landward migration and trough formation due to the shoreface nourishment, features absent in Delft3D-FM which exhibits an excessively flattened profile.

3.3.1 *Excessive flattening in present-day Delft3D-FM models*

The model results show that the conclusion drawn in past hindcast studies (Grunnet et al., 2004; Van Duin et al., 2004), conducted many years ago, is still relevant. These studies highlighted the unreliable cross-shore representation of shoreface nourishments in Delft3D with a flattened cross-shore profile.

Despite all updates in Delft3D, including the introduction of Delft3D-FM and the capability of conducting brute force simulations, which provide highly realistic boundary conditions, present-day Delft3D-FM models are still experiencing the same problems as nearly two decades ago.

Efforts that have been made to address this issue have primarily focused on adjusting model parameters or adjusting the numerical scheme to better capture the underlying physical processes involved. Despite these efforts, the fundamental problem of excessive flattening remains. This thesis proposes a new approach to achieve a more accurate representation of shoreface nourishment modelling: contrary to previous study efforts, the focus is not on improving the representation of physical processes involved, but on integrating a data-driven component into the process-based Delft3D-FM model to better capture the observed shoreface nourishment evolution.

3.3.1.1 *Temporal evolution of cross-shore flattening*

Figure 14 shows a rainbow plot illustrating the flattening of the cross-shore profile over time for Transect B. Within 100 days, the cross-shore profile completely flattens out. This rapid flattening stands in contrast to Jarkus observations, where the the crest height maintains, or even shows an increase in crest height in most cases, during approximately the first three to four years following a shoreface nourishment.

Figure 14: Rainbow plot of the evolution of the artificial flattening of the cross-shore profile for the first 100 days of morphological change visualized in intervals of five morphological days.

The rapid flattening of the nourishment may have implications for the overall morphological impact on the coast as modelled in Delft3D-FM. In Chapter 2, the lee and feeder effect of the nourishment was explained. As the observed nourishment maintains its crest for multiple years, the nourishment continues to exert the lee and feeder effect for an extended period of time, gradually decreasing its effect until the nourishment is fully diffused a few years later. In contrast, Delft3D-FM models show a completely diffused nourishment within 100 days after the construction, resulting in a less pronounced lee and feeder effect over the observed lifetime of a shoreface nourishment. The implications of these inaccuracies in cross-shore evolution on the morphological impact of the coast are investigated in Chapter 5.

3.3.1.2 *Redistribution of sediment*

In order to get a better understanding of the development of the nourishment as modelled in Delft3D-FM, the observed and modelled redistribution of the sediment after the first year of the nourishment is compared, as illustrated in Figure 15, showing the amount of erosion and sedimentation in m^3/m.

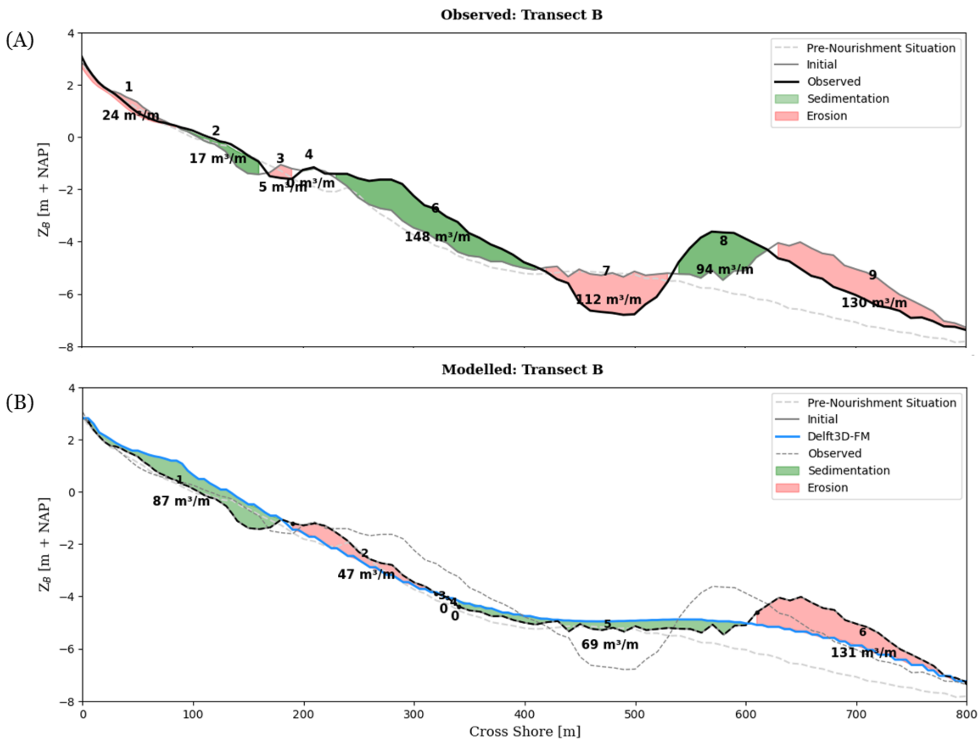


Figure 15: Observed and modelled sediment redistribution after one year of shoreface nourishment. (A) The observed profile retains 96% of the sediment in cross-shore profile; (B) the model retains 89% of the sediment in cross-shore. The model accurately predicts the sediment availability at the most seaward side (Area '6'), but inaccurately models the landward redistribution of this sediment volume.

Figure 15a shows that the profile's evolution aligns with the timeline as identified in Section 2.4: after one year, the cross-shore profile shows a milder seaward slope, a landward migration with an increase in crest height, and the formation of a trough. Furthermore, the observed profile experiences a total erosion volume of 260 m^3/m, and a cumulative sedimentation volume of 270 m^3/m. This means that 96% of the sediment stays in the cross-shore profile, and only 4% redistributes in alongshore direction.

Figure 15b shows the redistribution of sediment for the modelled profile. The model shows a total erosion volume of 177 m^3/m and a total sedimentation volume of 156 m^3/m, meaning that 89% of the volume remains in the cross-section, and 11% redistributes in the alongshore direction. This shows that for both the observed and modelled profile, the majority of the sediment remains in the cross-section of the profile, and only a small amount redistributes in alongshore direction.

Remarkably, the modelled amount of erosion at the most seaward side of the profile, denoted as Area '6' in Figure 15, is almost identical to the observed erosion in area 6. This means that the model performs well in predicting the sediment transport at the off-shore part of the profile. This is an important observation for the data-driven approach as described later in this thesis, as this morphological behavior in the deep water part of the cross-shore profile determines the amount volume of sediment available for redistribution over the profile.

While the model accurately predicts the sediment availability in the offshore part of the profile (area 6), the model shows deviations in the landward redistribution of this available sediment between the modelled and the observed profile. This observation suggests that a potential intervention with a data-driven approach to Delft3D-FM may only need to focus on intervening in the onshore-directed redistribution from the offshore part (area 6) of the profile.

3.4 CONCLUSIONS OF THE CASE STUDY

The case study shows that present-day process-based modelling of shoreface nourishments in Delft3D-FM still experiences a rapid flattening of the nourishment. Within 100 days of modelled morphological change, the nourishment is completely diffused. The redistribution of the sediment for both the modelled and observed occurs mainly in cross-shore direction as 96% and 89% of the sediment diffuses in cross-shore direction, respectively. Furthermore, the model accurately predicts the sediment availability in the offshore part of the profile, but shows deviations in landward redistribution of this sediment volume between the model and the observations.

The case study confirms that the conclusions from previous hindcast studies (Giardino et al., 2010; Grunnet et al., 2004; Van Duin et al., 2004) are still valid today. Therefore, in the remaining part of this thesis, a new approach to shoreface nourishment modelling is investigated: contrary to previous study efforts, the focus is not on improving the representation of physical processes and involved, but on incorporating a data-driven approach to more accurately represent the observed behavior in the modeling of the cross-section.

4 METHODOLOGY

This chapter provides the research methodology that is developed based on the Problem Analysis presented in Chapter 2 and Chapter 3. It introduces the hybrid model, presenting the modelling framework that integrates a data-driven component into the process-based numerical model Delft3D-FM, and elaborates on the methodology used to demonstrate its proof-of-concept trough a case study.

4.1 A HYBRID MODEL

4.1.1 *Model description*

A modelling framework is developed that combines the process-based numerical model Delft3D-FM with a data-driven component, aiming to enhance cross-shore modelling of shoreface nourishments by enriching process-based computations with data-driven input through Basic Model Interface (BMI).

The evolution of shoreface nourishments is strongly affected by three-dimensional (3D) processes that are currently not accurately incorporated in Delft3D-FM. Contrary to previous study efforts, the focus is not on improving the representation of these physical processes in Delft3D-FM, but on incorporating a data-driven component to more accurately represent observed behavior of cross-shore evolution in shoreface nourishment modelling.

By integrating the data-driven component through BMI, real-time interaction with Delft3D-FM is enabled that steers the process-based computations with data, aiming for model behavior that more closely resembles the observed evolution of a shoreface nourishment and prevents the excessive flattening of shoreface nourishments typically observed in standalone process-based models.

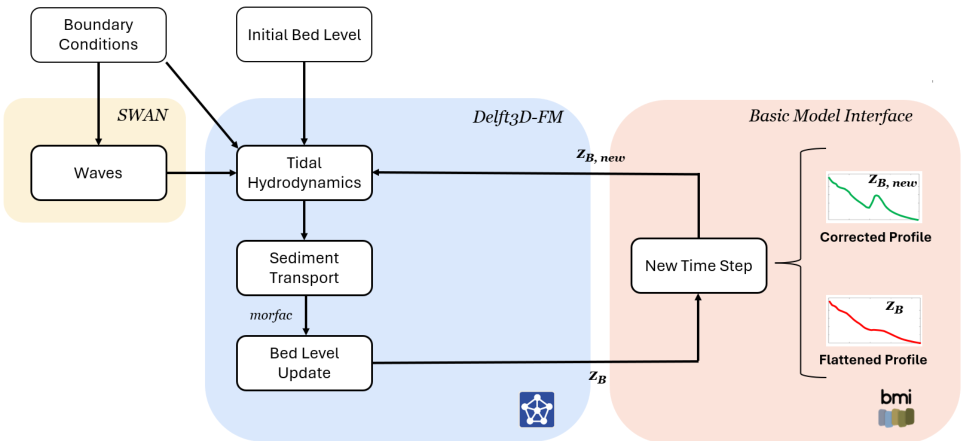


Figure 16: Overview of the hybrid model, showing the morphodynamic feedback loop applied in the model. Standard components from Delft3D-FM models are depicted in yellow (SWAN) and blue (Delft3D-FM) boxes. The addition of the data-driven component (orange) allows for manipulation of bed level updates made by Delft3D-FM, guiding the process-based computations with data to better represent observed shoreface nourishment evolution.

The hybrid model accomplishes this by adding a data-driven component to the morphodynamic feedback loop used in Delft3D-FM, see Figure 16. This morphodynamic feedback loop is fully described in Lesser et al. (2004) and therefore not further described here. The added data-driven component (orange component, see Figure 16) retrieves the updated bed level after each loop, corrects the bed level at the nourishment area based on data-driven manipulation methods described later, and then feeds this corrected data back into Delft3D-FM as input for its next timestep.

4.1.1.1 *Basic Model Interface*

The data-driven integration into Delft3D-FM is achieved via a component-based environment using Basic Model Interface (BMI). The BMI protocol (Hutton et al., 2020) operates by encapsulating models within a 'wrapper,' which acts as a secondary layer for managing simulations. This wrapper facilitates the seamless exchange of variables between model components during its simulation, thus enabling the control and manipulation of Delft3D-FM's behavior in real time. The work builds upon earlier studies that developed coupling tools for coastal applications, especially the work by Van Westen et al. (2024), whose code serves as a foundational basis that is adapted here.

The dynamic communication established between BMI and Delft3D-FM can be seen as lifting the hood of a car, revealing a new range of opportunities for in-depth exploration of current shortcomings and potential enhancements of Delft3D-FM by having the ability to take a real-time glimpse into the internal components of the model's engine.

4.1.2 *Model components*

The main objective of the hybrid model is to establish a method for manipulating Delft3D-FM's process-based computations with a data-driven controller. This involves fetching the bed level at a specified area of the grid, i.e. the nourishment area, followed by correcting the bed level and feeding this corrected data back into Delft3D-FM as input for its next timestep.

The modelling framework consists of three components that collectively drive the simulation process:

- Delft3D Flexible Mesh (FM): At the core of the framework lies Delft3D Flexible Mesh, a hydromorphodynamic model that calculates the water and bed level changes.
- SWAN: A wave model that computes random, short-crested wind-generated waves in coastal regions
- Data-driven controller (Controller): The controller is responsible for the data-driven manipulation of the bed level at the nourished area. It continuously monitors deviations between modeled and observed bed level changes within the nourishment area. If such deviations occur, it adjust the bed level as needed to steer the process-based computations to match observed shoreface nourishment evolution and enhance the reliability of the simulation data.

SWAN and Delft3D-FM operate with its own set of grid, boundary and initial conditions. The bed levels and water levels are calculated by Delft3D-FM, after which this data is transmitted to SWAN and the Controller. Subsequently, the Controller monitors and manipulates the bed level at the nourishment area, while SWAN updates the wave field.

4.1.2.1 *Seamless exchange of variables*

To further illustrate the information loop within the model, Figure 17 illustrates the flow of variables over time. The model operates in a loop-wise structure, characterized as follows:

1. The process begins with an update of SWAN, determining wave heights for the entire loop duration (which is set at 1200 seconds)
2. Subsequently, Delft3D-FM initiates its updates. Due to SWAN's larger timestep, FM executes multiple updates until it reaches the same time frame as SWAN.
3. SWAN then computes a new stationary wave field utilizing the water and bed levels obtained from Delft3D-FM.

4. The Controller receives the FM data and monitors and manipulates the data, after which the corrected bed level is feeded to Delft3D-FM again.

5. This loop continues continuously until the conclusion of the simulation period.

The exchange of variables is established by using a simple linear interpolation method, bridging between the BMI grid and the Delft3D-FM grid.

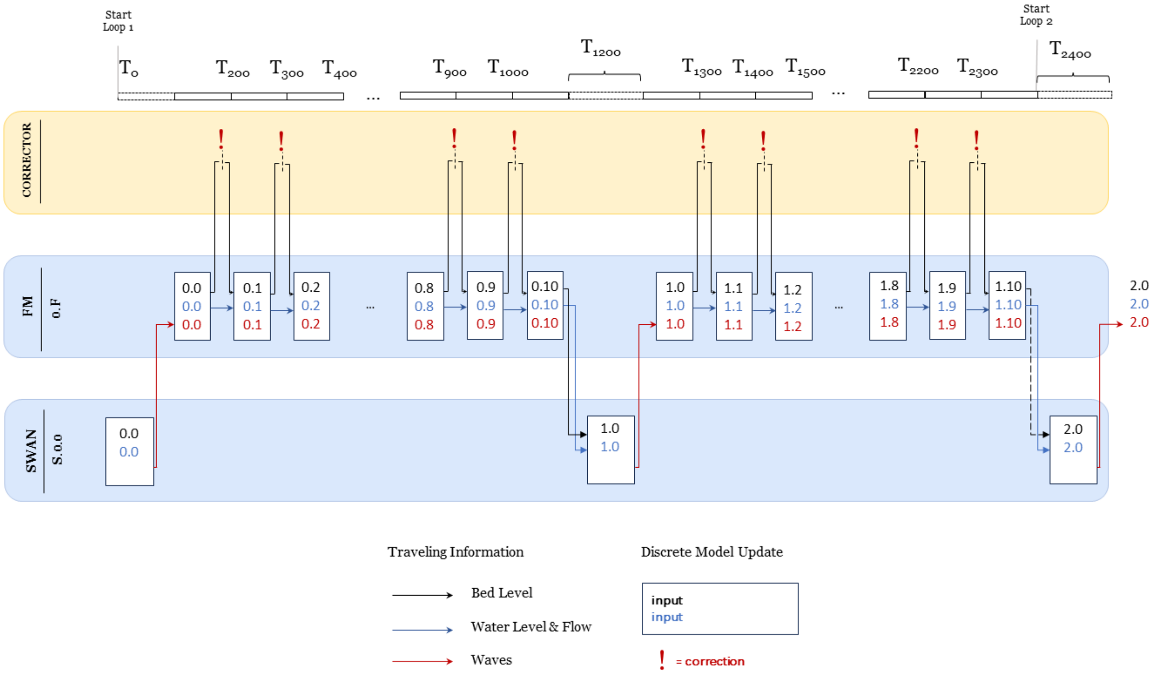


Figure 17: Information Loop of the model framework. The exchange of variables within the model framework involves three main components: Delft3D-FM, SWAN and the Controller. Arrows represent the transfer of updated variables. The numbers indicate the amount of time steps used as input for the models, counted from the last update of the higher-level sub-model. The flow of the framework is as follows: SWAN starts updating, then Delft3D-FM uses this wave field to update, which is then transferred to the Controller to manipulate the bed level. This process is continuously repeated. The figure is an adapted version of Velhorst (2017).

4.1.3 *Concept of the data-driven controller*

Within the model framework, a controller environment, in this thesis referred to as the 'Controller', is utilized. This controller is responsible for the data-driven manipulation of the hybrid model. Figure 18 illustrates the functionalities of the controller environment and its position within the simulation process. It can be seen that BMI starts the simulation process by initializing the grids and variables for each model in step 1 in Figure 18. Following this, variables are transferred from the Controller grid to the Delft3D-FM grid in step 2, changing from the controller environment to the Delft3D-FM component of the framework. Here it starts updating until it matches the simulation step of SWAN, as explained in Section 4.1.2.1. Once Delft3D-FM's updates are finalized, the bed level and other variables are exchanged from the Delft3D-FM grid back to the Controller grid in step 5.

In step 6, the Controller executes the data-driven correction by means of the Anchor Method (explained in the next section): it receives the bed level as calculated by Delft3D-FM and monitors deviations between the modelled and observed bed level changes within the nourishment area. Utilizing the freshly calculated bed level dataset from Delft3D-FM as input, which shows the tendency of flattening out, the Controller provides corrected cross-shore profiles that corresponds to measurements as output, reintroducing them back into the time loop, as visualized in Step 6 of Figure 18.

Following this step, the corrected bed level serves as input for a new iteration of the time loop, a process that is repeated continuously until the simulation reaches its user-defined end time.

Trough this Controller, users can steer Delft3D-FM's simulation according to their specified parameters. In this thesis, the primary application of this method is to replicate the observed evolution of a shoreface nourishment, as observed in Jarkus measurements, on a one-to-one basis.

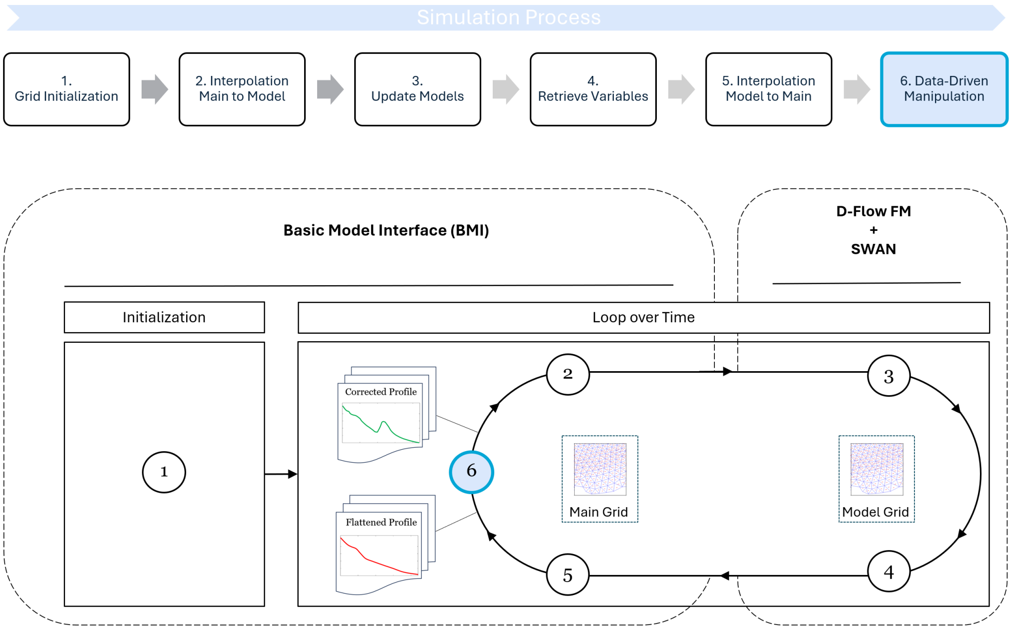


Figure 18: Data-driven correction. The figure illustrates the position of the data-driven correction within the model framework: (1) Initialization of grids and variables by BMI; (2) Transfer of variables from the Controller grid to the Delft3D-FM grid; (3) Updating of Delft3D-FM and SWAN; (4) Retrieving variables from Delft3D-FM and SWAN; (5) Exchange of updated variables from the Delft3D-FM grid back to the Controller grid; (6) Execution of data-driven correction by the Controller, monitoring deviations and providing corrected cross-shore profiles back into the loop for its next timestep.

4.2 METHODOLOGY FOR DEMONSTRATING PROOF-OF-CONCEPT

4.2.1 *Case Study: Ter Heijde*

To demonstrate the proof-of-concept of the hybrid model, the same case study as in Chapter 3 is used to evaluate the hybrid model's capabilities in manipulating the evolution of this shoreface nourishment. The aim is to replicate the evolution of this shoreface nourishment as measured in Jarkus surveys in Delft3D-FM, thereby highlighting the contribution of this thesis in implementing a data-driven component to the process-based Delft3D-FM model for shoreface nourishment modelling.

Furthermore, the case study at Ter Heijde is conducted with the hybrid model to explore the implications of inaccurate cross-shore modelling, as typically observed in standalone process-based models, on the accuracy of longshore predictions. To achieve this, both the hybrid model as the standard model are used to simulate and compare the morphological impact. By aligning the hybrid model with observed shoreface nourishment evolution, any differences with the standard model can provide insights into the implications of cross-shore inaccuracies on longshore predictions, thereby contributing to a better understanding of the potential added value of a hybrid model incorporating realistic cross-shore modeling.

4.2.2 *Model runs*

Table 4 provides an overview of the runs that are carried out to demonstrate the proof-of-concept and to evaluate the difference in modelled morphological impact of the shoreface nourishment between the hybrid model and standard model.

	Run	**Description**	**Model Version**
1.	Reference	Pre-nourishment situation (1997)	Standard model
2.	Nourishment	Initial situation post-nourishment (1998)	Standard model
3.	Nourishment	Initial situation post-nourishment (1998)	Hybrid model

Table 4: Model runs to demonstrate Proof-of-Concept and examine difference in modelled morphological impact between the hybrid model and standard model.

4.2.3 *Model set-up*

With the model set-up as described in Chapter 3, three months of morphological evolution of the shoreface nourishment is simulated with the hybrid model and standard model.

4.2.3.1 *Bathymetry*

Figure 19 and Figure 20 show the topview and cross-section, respectively, of the initial bathymetry used for the model runs (Table 4). The pre-construction situation serves as reference. The shoreface nourishment has a total volume of 882.605 m^3 with a longshore length of 1.7 km, which translates to a nourishment density of 517 m^3/m, and a width of 300 m, summarized in Table 5.

T_0	**Coastal Section**	**Jarkus Transects**	**Volume [m^3]**	**Density [m^3/m]**	**LxW [km]**	**Depth [m MSL]**
Aug-97	Delfland	9011315-9011485	882.605	517	1.7x0.3	-8 to -5

Table 5: Design of the shoreface nourishment at Ter Heijde

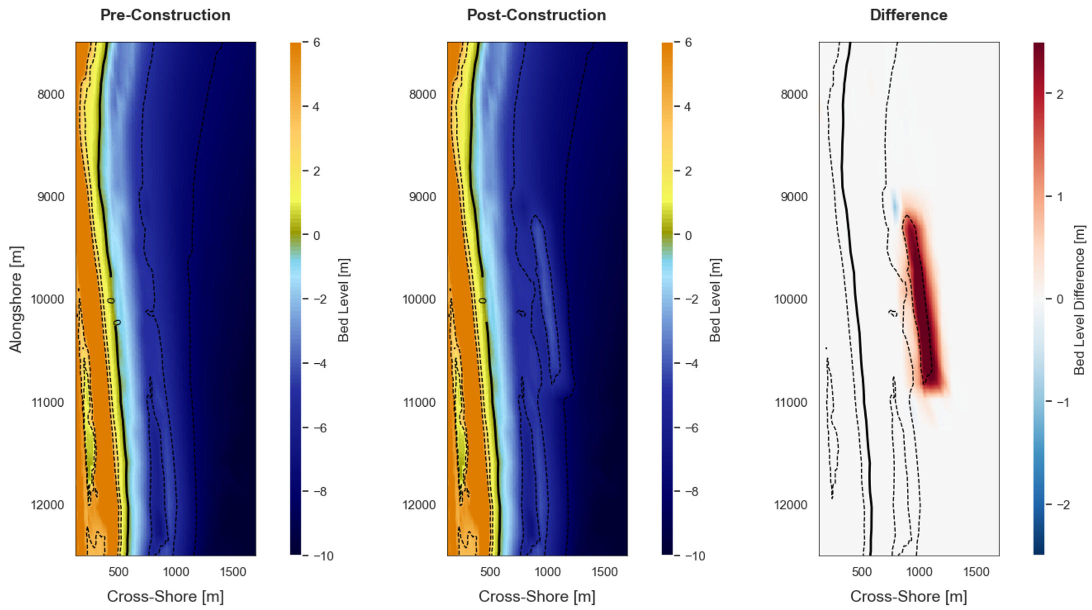


Figure 19: Simulated bathymetry for the Ter Heijde '97 shoreface nourishment showing the topview of the bathymetry for the reference situation, the shoreface nourishment and the difference between these two (nourished – unnourished situation).

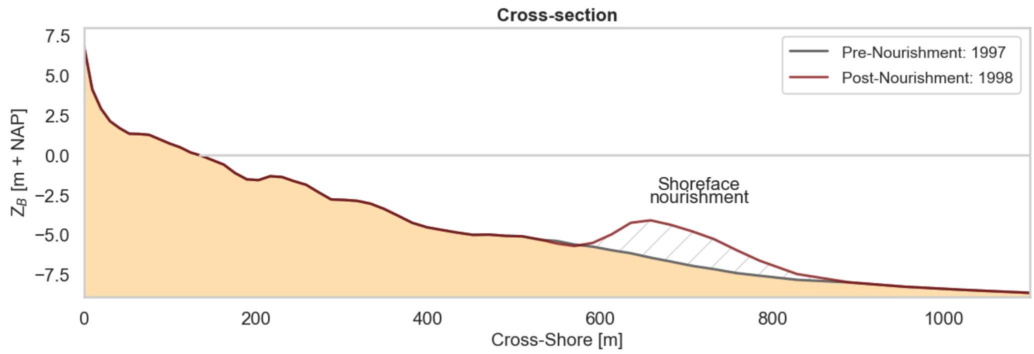


Figure 20: Simulated cross-shore morphology for the nourished and unnourished situation of the central transect as implemented in the hybrid model.

4.2.4 *Implementation of the data-driven manipulation*

4.2.4.1 *The Anchor Method*

The main method that is used for the data-driven manipulation carried out in the hybrid model for this case study is referred to as the Anchor Method.

This method involves selecting specific grid cells as anchor points, from which data is retrieved from Delft3D-FM and adjusted during execution. By controlling the bed level in these grid cells, the method enables the reproduction of observed nourishment evolution.

In order to set up the data-driven manipulation for the hybrid model applied to the Ter Heijde '97 shoreface nourishment, the following two steps are followed:

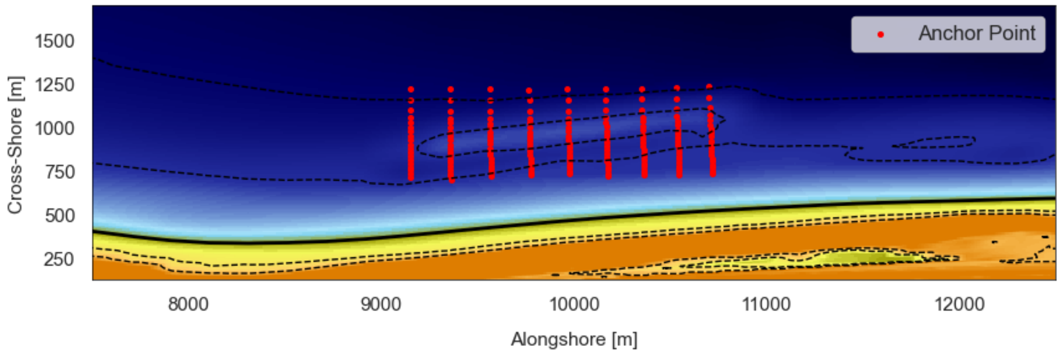
1. Selecting the amount and location of the anchor points;
2. Creating Δ_z-curves derived from Jarkus measurements that drive Delft3D-FM's bed level changes at each selected anchor point.

After these steps, the simulation will start running, with Delft3D-FM computations being overwritten with data from the Δ_z-curve for each timestep at each anchor point.

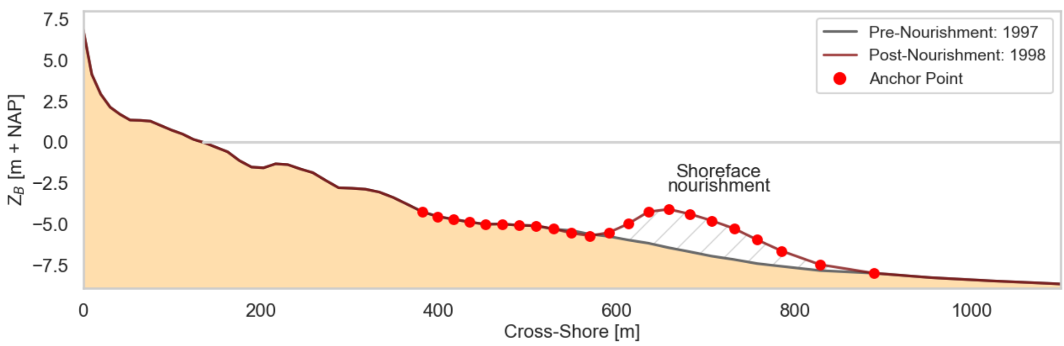
Step 1: Selecting the amount and location of anchor points

In order to manipulate the shoreface nourishment evolution in the hybrid model, anchor points (i.e. grid points) are selected for which the bed level updates are steered during simulation.

To reproduce the evolution as seen in Jarkus measurements for the case study, a total of 180 anchor points divided over nine cross-shore transect over the nourishment are selected, see Figure 21. The high amount of anchor points ensures that the evolution of the shoreface nourishment as observed in Jarkus measurements is fully reproduced in the simulation. For these selected points, the bed level changes computed by Delft3D-FM are overwritten with values from the Δ_z-curve, which is derived from Jarkus measurements (see next step).



((a)) Top view; red dots depict anchor points



((b)) Cross-section; red dots depict anchor points

Figure 21: Simulated bathymetry for the case study, in which red dots indicate the anchor points used in the data-driven manipulation for the hybrid model. In these points the bed level is steered based on Jarkus measurements.

Step 2: Creating Δ_z-curves that drive Delft3D-FM's bed level changes

For each anchor point, a Δ_z-curve is created based on Jarkus measurements (see Figure 50). A Δ_z-curve is a smooth line fitted through the yearly measured Jarkus bathymetries, and interpolated to the location of each anchor point, to convert yearly measured data points to timestep-level data at the anchor point location in a smooth way (see Section D.4 for a more detailed description). It stores bed level information for each timestep, which is then provided to the anchor points in Delft3D-FM. These curves guide the bed level evolution by overwriting Delft3D-FM's computed bed level changes at the selected anchor points, and prevents the nourishment from flattening out excessively.

The model setup undergoes a simulation period of three months of morphological changes to reproduce the measured evolution of the shoreface nourishment in the hybrid model. The objectives are to (1) demonstrate the Proof-of-Concept of the model framework and (2) to investigate the implications of inaccurate cross-shore modelling on the accuracy of the representing the morphological impact of a shoreface nourishment in Delft3D-FM.

5

RESULTS

This chapter demonstrates the proof-of-concept of the hybrid model. Additionally, it presents the differences in computed morphological impact between the hybrid model and the standard model, using the shoreface nourishment at Ter Heijde as a case study. The aim is to explore the added value of integrating a data-driven component into Delft3D-FM, and to better understand the consequences of inaccuracies in cross-shore modelling on longshore morphological predictions.

5.1 PROOF-OF-CONCEPT

This section demonstrates the proof-of-concept for the hybrid model, and is divided into two sections for which the hybrid model and standard model are shown. Section 5.1.1 shows the results for the topview, while Section 5.1.2 presents the cross-section after three months of modelled morphological changes.

5.1.1 *Top view*

The top view of the initial bathymetry, and the bathymetry for the hybrid model and the standard model after three months of morphological modelling, along with the difference between them are shown, see Figure 22. The shoreface nourishment is almost completely diffused for the standard model, while the hybrid model demonstrates its ability to maintain its nourishment shape.

In the fourth subplot, the difference (hybrid - standard) between the hybrid model and the standard model is presented, see Figure 22. The results reveals a negative bed level difference (blue zone) landward of the initial nourishment location compared to the standard model, and a positive bed level difference on top of the initial nourishment location. This pattern suggests the formation of a trough for the hybrid model in the blue zone, and the increase or maintenance in crest height in the red zone, features absent in the standard model due to its tendency to flatten out.

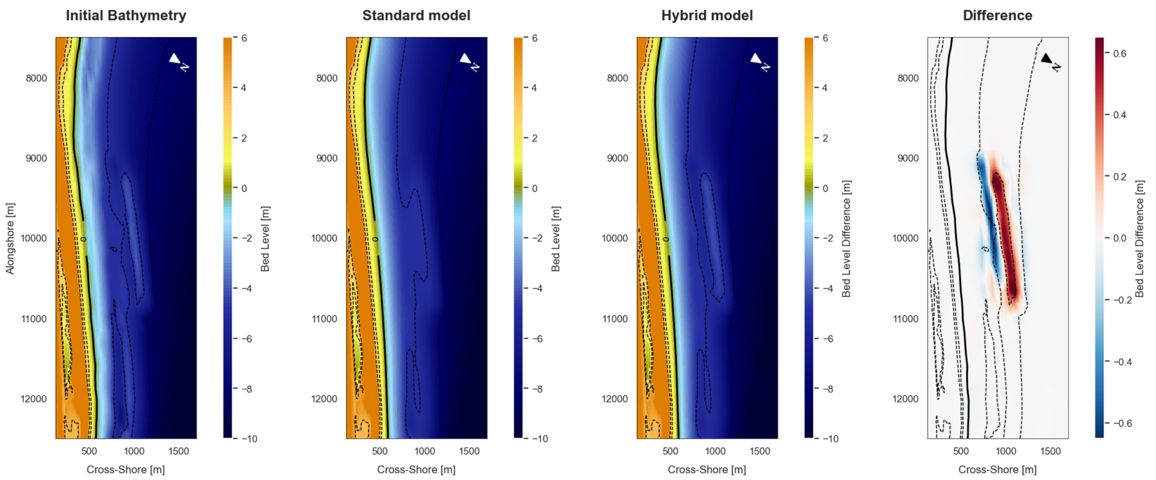


Figure 22: Proof-of-Concept: topview. The morphology of the initial situation, along with the bathymetry for the hybrid model and the standard model after three months of modelling, and the difference between those (hybrid – standard). The hybrid model maintains its shape while the standard model shows nearly complete diffusion of the nourishment. Black contourlines in the fourth panel show the initial bathymetry.

5.1.2 *Cross-shore view*

Figure 23 presents the cross-shore profile for the pre-nourishment bathymetry, the initial bathymetry, and the bathymetry for the hybrid model and the standard model after three months of morphological modelling.

The standard model shows excessive flattening, resulting in a rapid loss of its nourishment shape. In contrast, the cross-shore profile of the hybrid model shows no excessive flattening: it maintains its nourishments shape.

Furthermore, the hybrid model shows behavioral characteristics of shoreface nourishment evolution that were outlined in Section 2.4.2. The four characteristics were identified as: (1) landward shift and crest height increase (i.e. not rapidly diffusing), (2) milder seaward facing slope, (3) steeper landward facing slope and trough formation, and (4) resumption of natural bar cycle after four to five years.

The hybrid model clearly shows the representation of characteristic (1), (2) and (3) after three months of morphological modelling, see Figure 23.

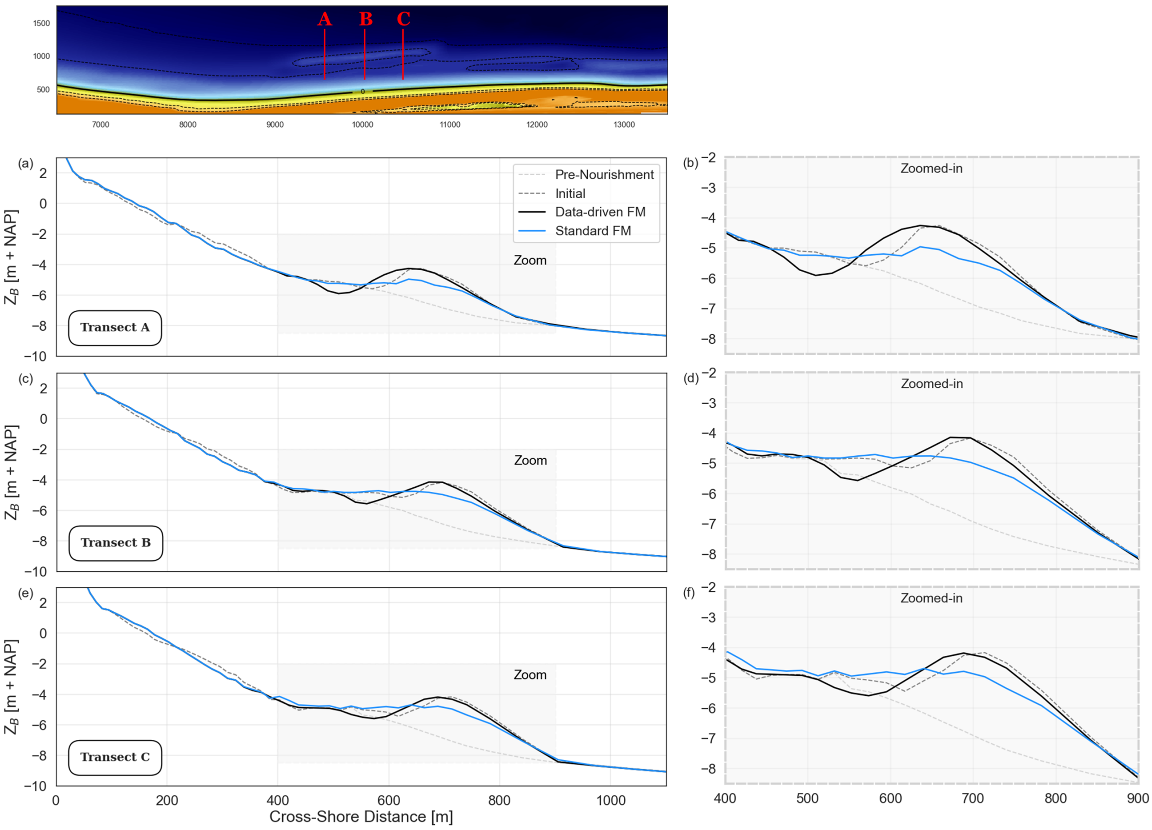


Figure 23: Proof-of-Concept: cross-shore view. Cross-shore profiles showing the pre-nourishment bathymetry, initial bathymetry, and bathymetry after three months of morphological for the hybrid model and the standard model. The standard model exhibits excessive flattening, while the hybrid model maintains its nourishment shape. The model demonstrates its ability to represent behavioral characteristics of shoreface nourishment evolution: landward shift and crest height increase, milder seaward slope, and steeper landward slope with trough formation.

5.1.3 *Temporal evolution of the cross-shore profile*

The hybrid model results show a different temporal evolution compared to the standard model results, see Figure 24. For the hybrid model, the formation of a trough is visible, while the crest increases in height and migrates landwards. In contrast, the standard model shows flattening of the cross-shore profile.

The process of flattening of the cross-shore profile in the standard model is not smooth: the vertical displacement is irregular, suggesting a dependency on forcing conditions. Further discussion on this aspect is provided in Section 5.4.

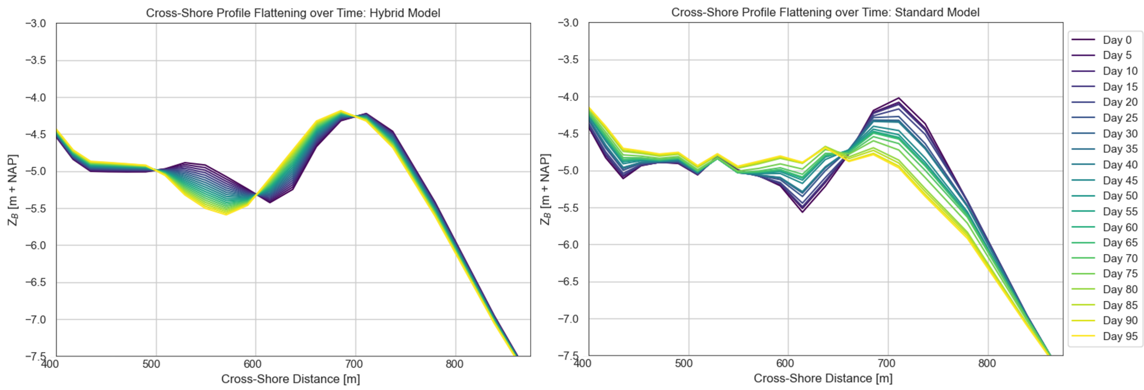


Figure 24: Rainbow plot depicting the evolution of the cross-shore profile for the first 100 days of morphological change visualized in intervals of five morphological days. Hybrid model results show the formation of a trough, along with the increase and landward shift of the crest, while the standard model displays excessive flattening of the cross-shore profile.

From Figure 22, Figure 23 and Figure 24 the following behavioral characteristics of a shoreface nourishment can be identified for the data-driven approach to Delft3D-FM:

- The hybrid model does not show rapid flattening as observed in the standard model. After three months of morphological simulation, the nourishment shape is still clearly visible.
- The hybrid model shows a landward shift and crest height increase, aligning with characteristic 1 identified in Section 2.4.2.
- The hybrid model shows a milder seaward facing slope, aligning with characteristic 2 identified in Section 2.4.2.
- The hybrid model shows a steeper landward facing slope and trough formation, aligning with characteristic 3 identified in Section 2.4.2

The hybrid model results successfully demonstrate the proof-of-concept by representing the behavioral characteristics of shoreface nourishment evolution outlined in Section 2.4.2.

5.2 COASTAL IMPACT

This section examines the impact of the hybrid model on nearshore morphology. In Section 5.1, the proof-of-concept of the hybrid model is demonstrated, and unlike the standard model, the hybrid model maintained its nourishment shape and followed the observed cross-shore evolution over three months of morphological modelling for the case study at Ter Heijde.

In this section, the consequences of incorporating a data-driven component that aligns more closely with observed cross-shore evolution are examined. For this purpose, the difference in modelled coastal impact between the hybrid model and the standard model is discussed. By aligning the hybrid model with observed shoreface nourishment evolution, any differences with the standard model can provide insights into the implications of cross-shore inaccuracies on longshore predictions, thereby contributing to a better understanding of the potential added value of a hybrid model.

The comparison of coastal impact between the models is achieved by evaluating the relative impact of the hybrid model and the standard model, which helps to identify sedimentation and erosion patterns caused solely by the nourishment volume. The relative impact is defined as the difference between the nourishment case and the reference case (nourishment case - unnourished case).

5.2.1 *Reference case*

To evaluate the relative impact of the nourishment volume as modelled with the hybrid and standard model, first a baseline is established. The unnourished situation is the reference for studying the impact of the nourishment. This reference case is modelled with the standard model and incorporates the pre-nourishment bathymetry data obtained from 1997 Jarkus measurements.

Figure 25 shows the initial and final bathymetry, and the difference between them as modelled with the standard model.

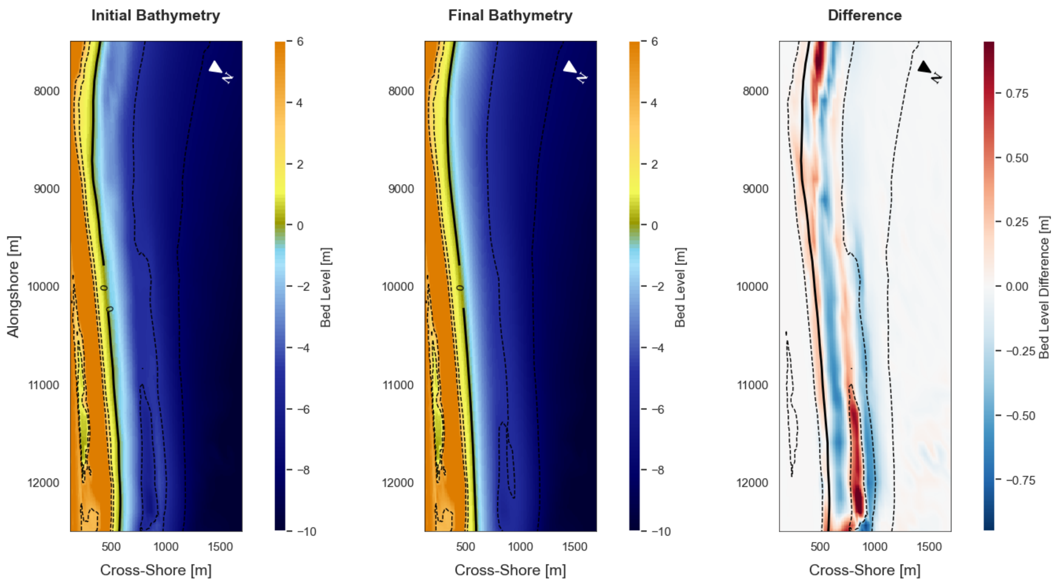


Figure 25: Reference Case: the initial and final bathymetry, and the difference between them as modelled with the standard model after three months of bruteforce simulation. Black contourlines in the third panel show the initial bathymetry.

5.2.2 *Morphological impact: standard model*

The nourishment is then added to the reference situation. Figure 26 shows the initial and final bathymetry, and the difference between them, as modelled with the standard model.

Furthermore, the initial and final relative impact of the nourishment, i.e. the difference (nourishment case - unnourished case) between bathymetries for the nourished and unnourished case is presented (see Figure 27) This relative impact can be seen as the morphological impact caused solely by the nourishment volume.

The nourished sand has diffused partly in the cross-shore and longshore direction, but most sand is transported in onshore direction. The nourishment does not show any longshore migration. Additionally, increased sedimentation occurs in the lee of the nourishment, see third panel of Figure 27, and increased erosion occurs downdrift of the nourishment, aligning with the with the general lee- and feeder effects of a shoreface nourishment, as discussed in Section 2.1.

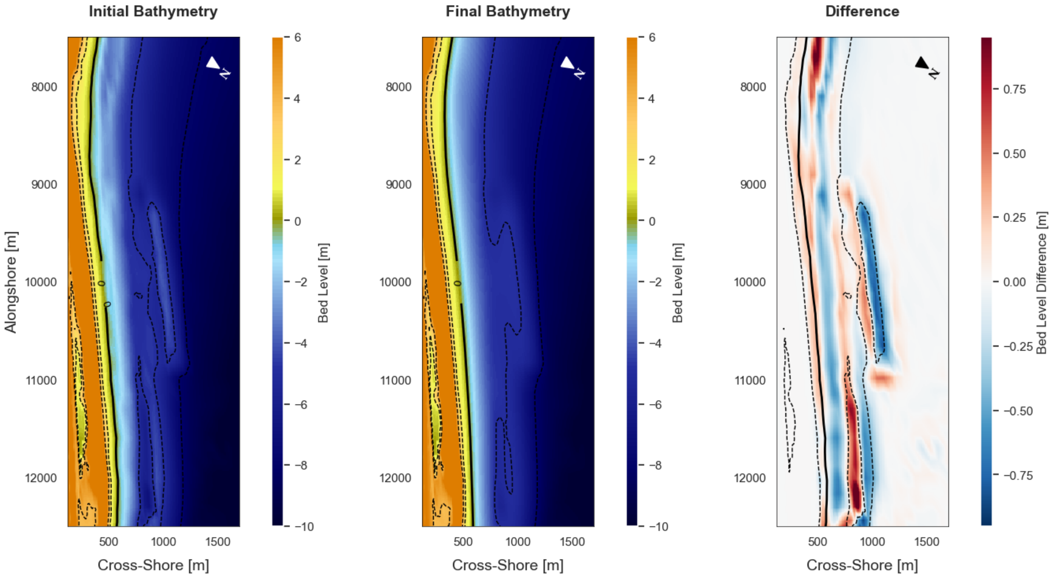


Figure 26: Nourished case: standard model. The initial and final bathymetry, and the difference between them as modelled with the standard model after three months of bruteforce simulation. Black contourlines in the third panel show the initial bathymetry. Computed by the standard model.

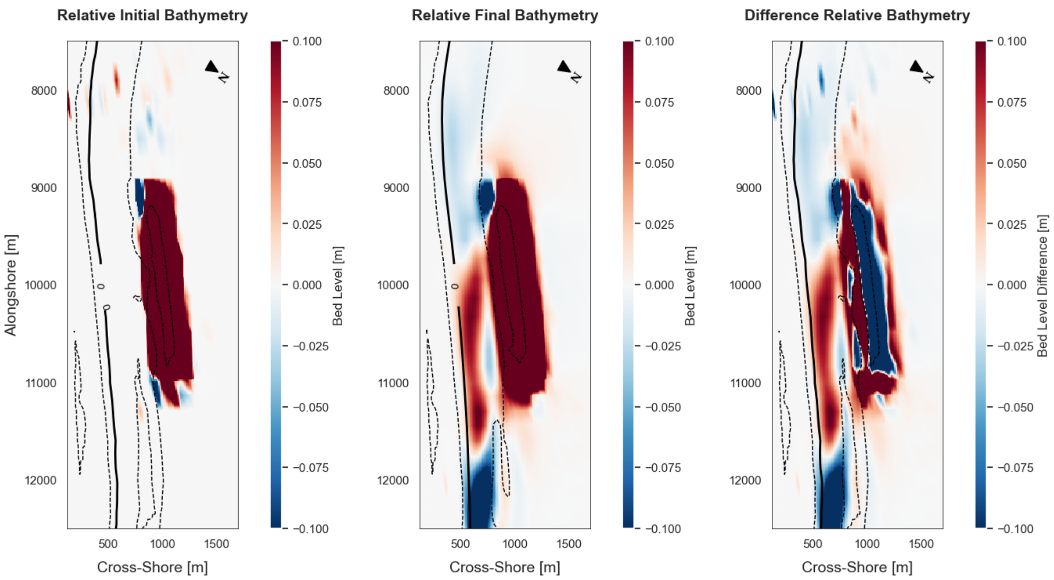


Figure 27: Nourished case: standard model. Initial and final relative impact of the nourishment, i.e. the difference between nourished and unnourished case, after three months of bruteforce simulation. The nourishment provides its lee and feeder effect resulting in sedimentation in the lee of the nourishment and erosion downdrift of the nourishment. Black contourlines show the initial bathymetry. Computed by the standard model.

5.2.3 *Morphological impact: hybrid model*

Again, the nourishment is added to the reference case. However, this time the hybrid model is used to compute the morphological evolution. Figure 28 shows the initial and final bathymetry, and the difference between them, as computed by the hybrid model.

Additionally, Figure 29 shows the initial and final relative impact of the nourishment, i.e. the difference (nourishment case - unnourished case) between bathymetries for the nourished and unnourished case. This relative impact can be seen as the morphological impact caused solely by the nourishment volume.

Once again, sedimentation occurs in the lee of the nourishment, and erosion downdrift of the nourishment, caused by the nourishment volume. The morphological response of the hybrid model aligns with the standard model on spatial scales in the order the nourishment, but on smaller spatial scales differences are observed, see next section.

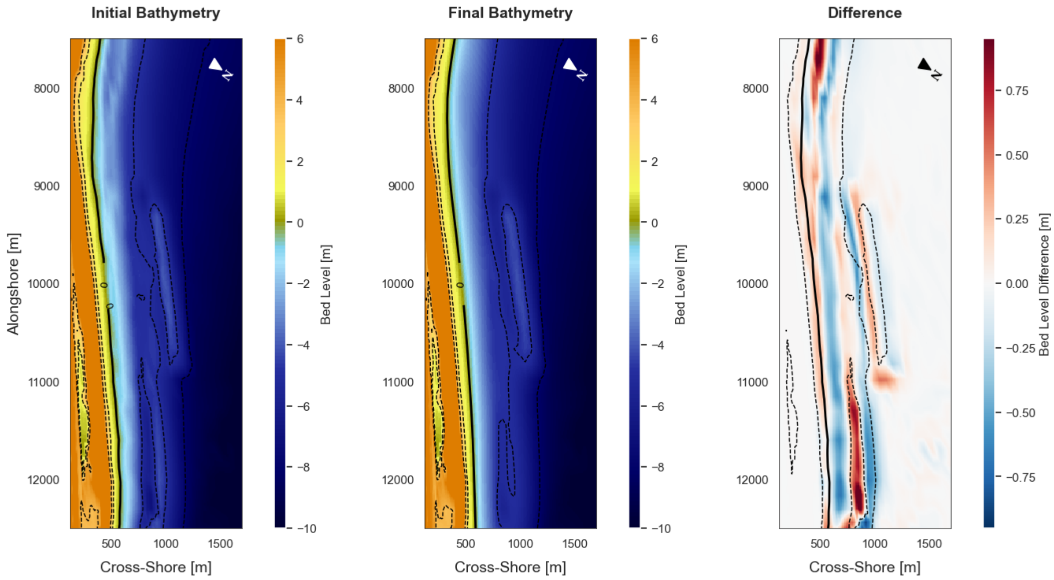


Figure 28: The initial and final bathymetry, and the difference between them as modelled with the hybrid model after three months of bruteforce simulation. Black contourlines in the third panel show the initial bathymetry. Computed by the hybrid model.

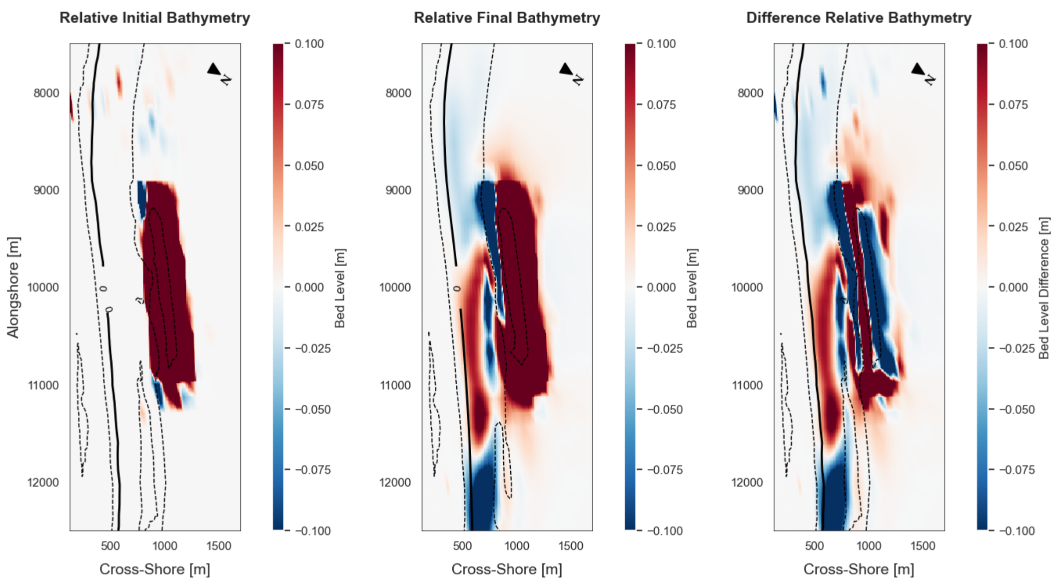


Figure 29: Initial and final relative impact of the nourishment, i.e. the difference between nourished and unnourished case, after three months of bruteforce simulation. The nourishment provides its lee and feeder effect resulting in sedimentation in the lee of the nourishment and erosion downdrift of the nourishment. Black contourlines show the initial bathymetry. Computed by the hybrid model.

5.2.4 *Difference in morphological impact: hybrid model vs standard model*

To investigate the impact of the hybrid model on morphological predictions, the difference between the hybrid model and the standard model is investigated, see Figure 30. The figure shows the final bathymetry as computed by the standard model (first panel, see Figure 30) and hybrid model (second panel), as well as the difference (hybrid - standard) between them (third panel).

Comparing the models (third panel, see Figure 30) reveals a difference in sedimentation and erosion patterns. Firstly, the standard model overestimates the amount of erosion at the initial nourishment location compared to the hybrid model. Additionally, distinct zones at the coastline can be observed in the lee of the nourishment and downdrift of it that show differences between the models. In the lee of the nourishment, two red zones can be distinguished between x=9200 m to x=9900 m and from x=9200 m to x=9900 m for which the hybrid model computes more sedimentation. In between those zones (from x=9900 m to x=11000 m) a zone with less sedimentation can be observed. Downdrift of the nourishment, less erosion is observed (red zone; from x=11000 m to 11500 m) and a zone with more erosion further downdrift (blue zone; x=11500 m to x=12300 m).

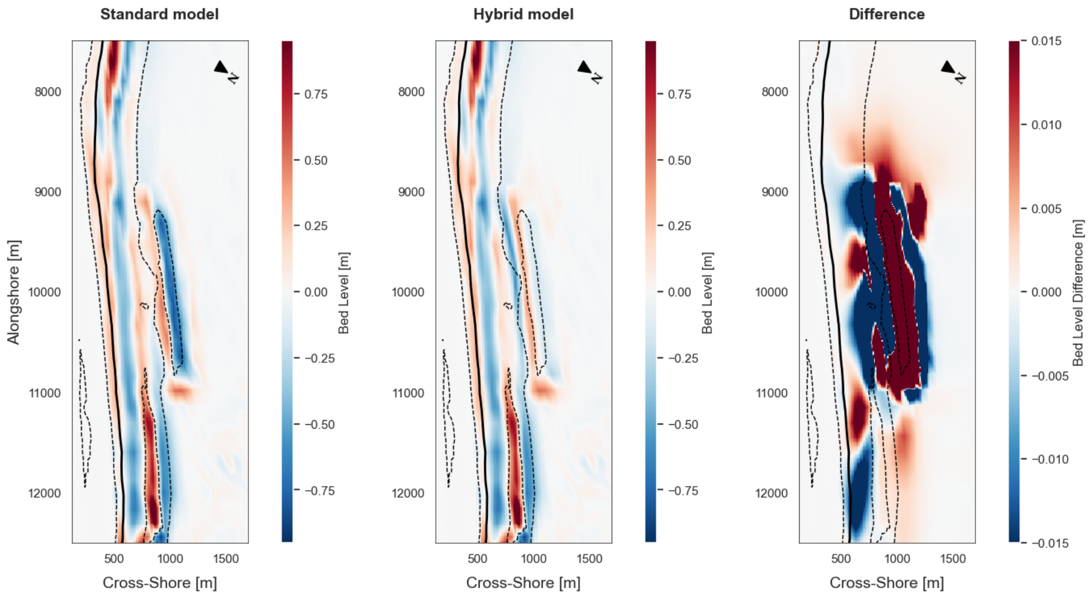
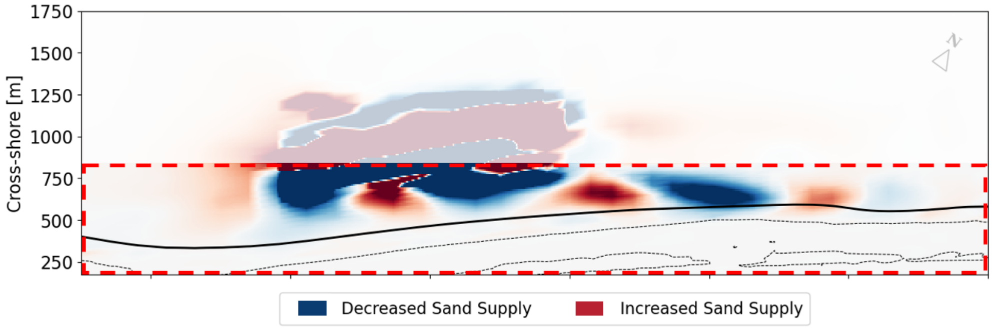


Figure 30: Comparison of morphological impact: hybrid model vs standard model. The hybrid model shows increased sedimentation in the lee and increased erosion downdrift of the nourishment, which can be attributed to the increased wave sheltering resulting from preventing excessive flattening of the nourishment.

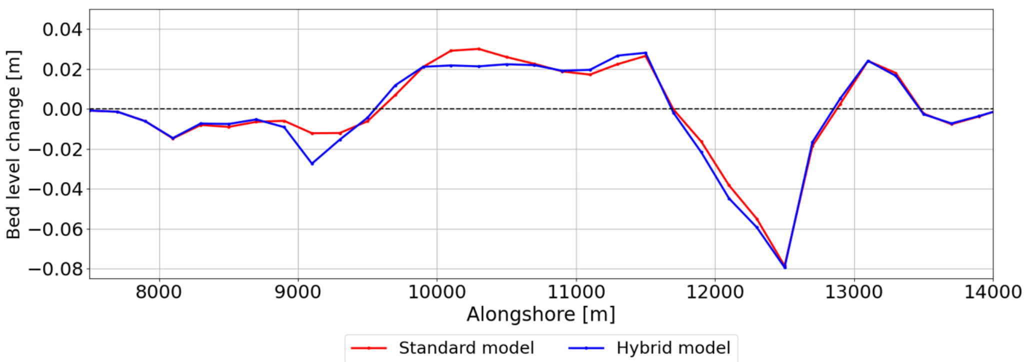
5.2.4.1 *Cross-shore averaged bed level changes*

Alongshore variations in sedimentation and erosion are explored for the hybrid and standard model to examine the implications of cross-shore inaccuracies in shoreface nourishment modelling on the longshore direction, see Figure 31. The cross-shore averaged bed level changes are calculated for zone close to the coastline (0 m < y < 750 m), illustrated by the red box in Figure 31a.

By averaging over the cross-section in this zone, the results shows that while overall patterns of sedimentation and erosion in a spatial scale in the order of the nourishment match between the hybrid model and the standard model, there are noticeable differences in magnitudes on smaller scales. For example, between x=9200 m to x=9400 m, significantly more erosion is predicted for the hybrid model compared to the standard model. Furthermore, the sedimentation in red box 1 is significantly larger in the hybrid model, while also difference can be observed in sedimentation between boxes 2 and 3.



((a)) Bed level difference (hybrid - standard)



((b)) Cross-shore averaged bed level changes

Figure 31: Comparison of bed level changes for zone close to the coastline (dashed red box) between the hybrid model and standard model. (a) illustrates the difference in sedimentation and erosion patterns between the models, and (b) shows the cross-shore averaged bed level changes.

5.2.5 *Temporal evolution of differences between models*

To quantify the impact of the hybrid model, the difference between the hybrid model and standard model averaged over each sedimentation / erosion zone is computed (see Figure 32a). The top panel (Figure 32a) shows the percentage difference after three months of morphological modelling. The differences in sedimentation / erosion patterns in longshore direction between the hybrid model and the standard model, attributed to the nourishment volume only, are between 10-26% after three months of morphological modelling.

For the leftmost red box (Box A; ranging from approximately x=9400 m to x=10000 m), the hybrid model predicts 26% less erosion compared to the standard model. Similarly, there is 20% more erosion estimated for the adjacent box (Box B; approx. x=10000 m to x=10800 m). For Box C (x=10800 m to x=11500 m), the hybrid model computes 9% more sedimentation. Additionally, there is 13% less sedimentation in the Box D from x=11500 to x=12400 m, and 26% more sedimentation in Box E.

Interestingly, the difference between hybrid model and standard model increases over time (Figure 32b). This divergence is due to the rapid flattening of the nourishment after construction in the standard model, while the hybrid model does not show rapid flattening and shows a more gradual shoreface nourishment evolution, which aligns with Jarkus observations. Consequently, the difference between the models gradually increases, and this difference is expected to increase further over time as a positive trend is observed for the differences (see Figure 32b).

The findings are based on just three months of morphological modelling. As shown in the rainbow plot in Figure 24, the nourishment is almost completely flattened out at the three month mark in the standard model, resulting in negligible lee effect from this moment onward. On the contrary, hybrid model continues to include the lee effect throughout most of the nourishment lifetime (4-5 years). Consequently, the results between the models will keep diverging, indicating potential for significant differences in both cross-shore and longshore direction between the models over a prolonged time period.

By incorporating a more realistic cross-shore shoreface nourishment evolution into the model (i.e., avoiding excessive flattening) through the integration of a data-driven component in Delft3D-FM, the maintenance of the nourishment results in a more pronounced representation of the lee effect. This process causes the difference between the hybrid model and the standard model to increase over time, as indicated by the positive trend in Figure 32.

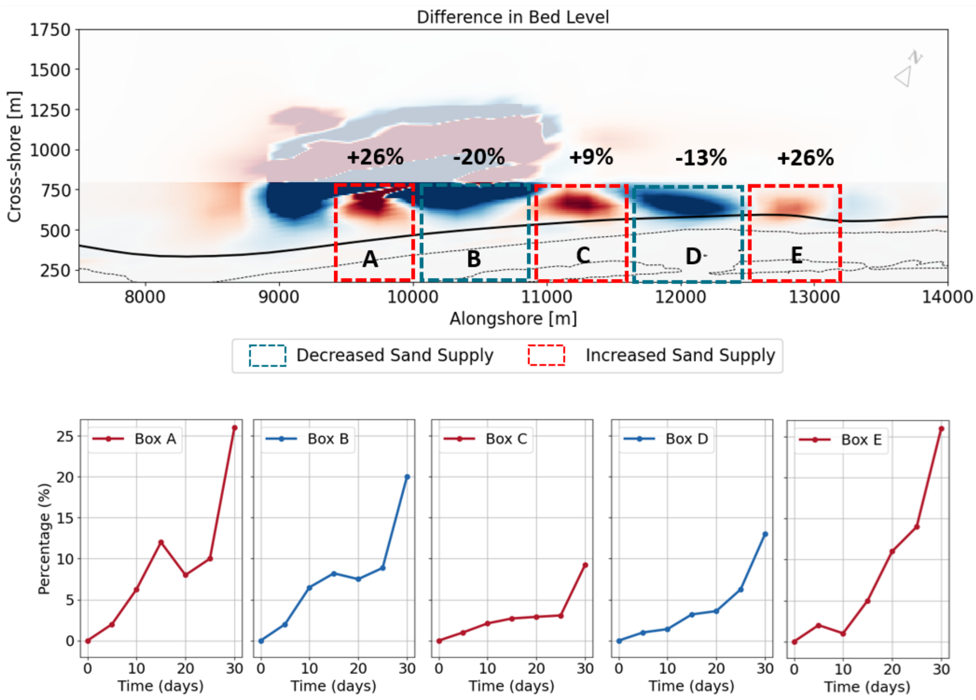


Figure 32: Comparison between the hybrid model and standard model. (a) Percentage difference averaged over each sedimentation/erosion zone. (b) Positive trend indicating increasing divergence between the models over time.

This indicates that:

- There is a trend of increasing difference between the hybrid model and standard model;
- The behavior of the distinct areas characterized by sedimentation or erosion remain constant over the simulation period: areas that experience sedimentation continue to do so, and areas with erosion keep exhibiting erosion. This pattern does not change over time.

These points indicate that the impact of the hybrid model increases over time, implying that its added value will continue to grow over time as well.

5.3 GOVERNING PROCESSES

This section elaborates on the governing processes that lead to differences in computed coastal impact between the hybrid model and the standard model, based on two types of runs: short runs of one day and long-term runs of three months. The short runs are used to analyze the influence of the hybrid model on hydrodynamics (flow and waves) under both storm and normal conditions. The longer runs are used to demonstrate the cumulative coastal impact governed by the the difference in hydrodynamics between the hybrid and standard model over an extended period.

5.3.1 *Wave heights*

To evaluate the hybrid model's influence on wave height, wave heights are studied under storm and normal conditions (H_{m0} ranging from 1 to 4m) from the north-west direction. Figure 33 shows the wave height computed by both the standard and hybrid model under these varying wave conditions. These simulations use the final bathymetry of the long-term three-months runs, as seen in Section 5.1.3, as initial bathymetry. The aim is to illustrate the impact of the hybrid model, which incorporates realistic cross-shore evolution, on the hydrodynamics acting at the shoreface nourishment, and to compare it with the standard model that excessively flattens the bathymetry.

Results show that during high wave conditions, differences in wave heights are observed between the hybrid and standard model in the lee of the nourishment, see Figure 33. While both models compute (partial) wave breaking at the shoreface nourishment for larger waves (H_{m0} = 2m, 3m and 4m), the hybrid model shows more pronounced wave breaking, resulting in a reduction of wave height and thus a calmer wave climate shoreward of the nourishment, see middle and lower plots of Figure 33. In contrast, smaller waves (H_{m0} = 1m) are able to propagate over the nourishment without breaking in both models, resulting in no differences between the hybrid model and standard model, see upper plots of Figure 33.

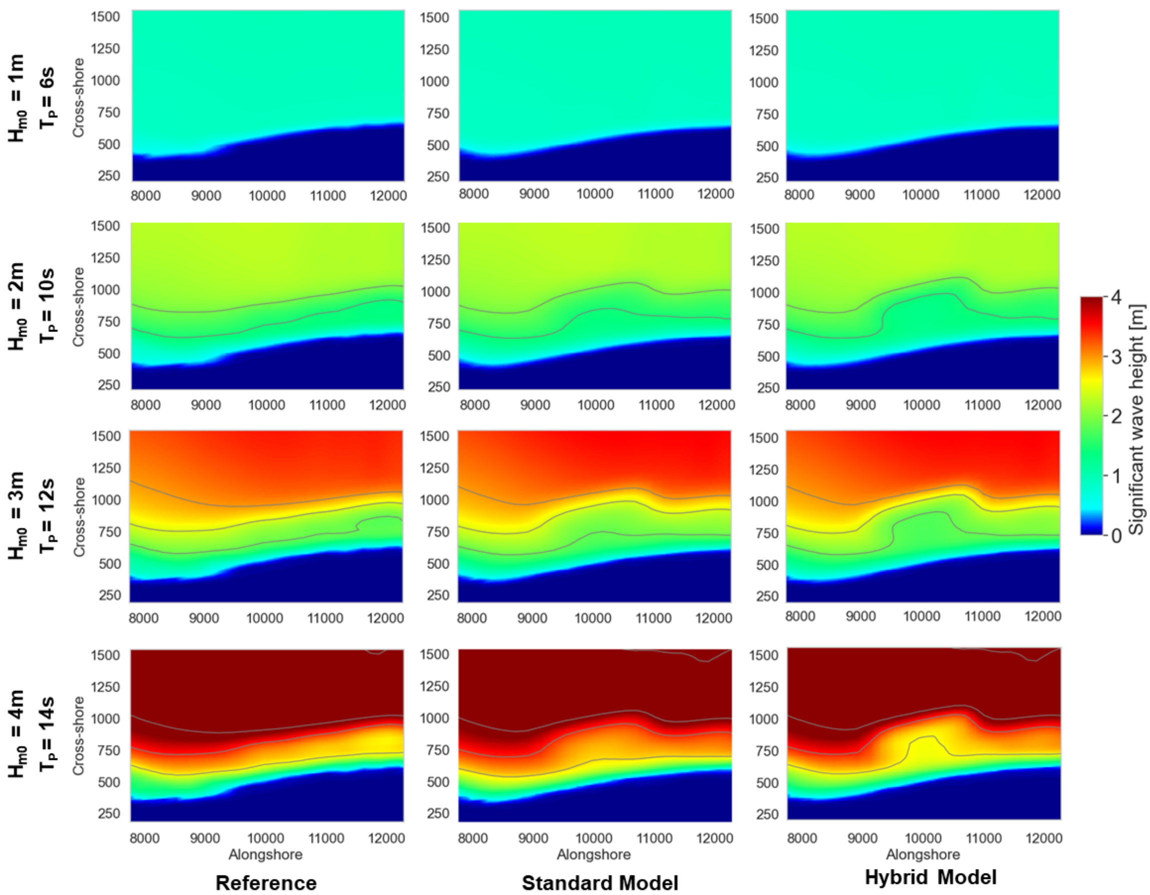


Figure 33: Wave transformation under varying wave conditions (H_{m0} ranging from 1 to 4m) computed by the standard and hybrid model, using the final bathymetry from long-term simulations as the initial bathymetry.

5.3.1.1 *Alongshore transect*

To further illustrate the more pronounced wave sheltering in the hybrid model compared to the standard model, the wave heights are calculated along an alongshore transect, illustrated by the black dashed line in Figure 34. This alongshore transect plots wave heights for high (H_{m0} = 3m) northwest wave conditions, comparing the hybrid model with the standard model and the pre-nourishment situation. The shoreface nourishment is located approximately between alongshore distance x=9200 m and x=10800 m.

Under these wave conditions, significant differences in wave height appear between the models in the lee of the nourishment, see Figure 34. Between alongshore distance x=9200 m and x=10800 m, coinciding with the lee of the nourishment, wave heights computed by the hybrid model are approximately 15-20% lower than in the standard model, almost doubling the reduction of wave height. The key factor driving these differences lies in the fact that the hybrid model incorporates realistic cross-shore evolution, while the nourishment crest in the standard model flattens excessively. This causes waves to break earlier and/or more frequently in the hybrid model, consequently leading to a calmer wave climate in the lee of the nourishment for the hybrid model.

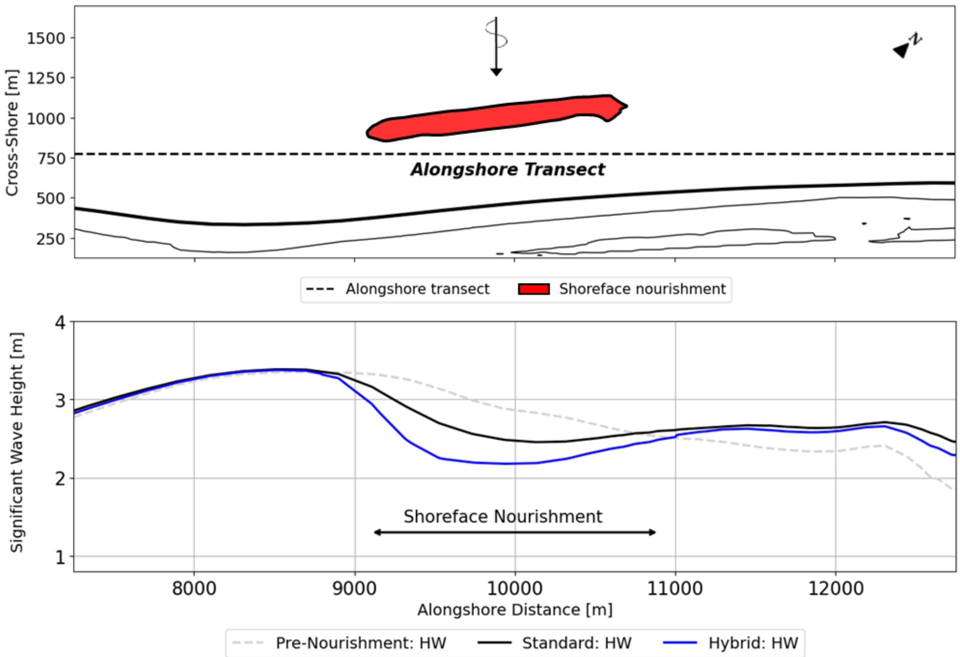


Figure 34: Wave height comparison under high (HW; H_{m0} = 3m) northwest wave conditions. The hybrid model shows 15-20% lower wave heights in the lee of the nourishment, leading to a more pronounced wave shadow zone.

5.3.2 *Flow velocities*

To assess the the influence of the hybrid model on flow velocity, the flow velocity is calculated for the hybrid model and the standard model under low and high wave conditions from the northwest (normally incident waves). The difference in wave height, particularly the more pronounced wave shadow zone computed in the hybrid model, directly impacts the flow velocities resulting in a calmer wave climate shoreward of the nourishment, see Figure 35 and Figure 36.

Conditions with small wave heights (H_{m0} = 1m) result in no significant differences between the reference run, standard model and hybrid model, as the waves propagate over the nourishment without breaking. However, for higher wave heights (H_{m0} = 2m, 3m and 4m), the hybrid model shows a reduction in flow velocity in the lee and intensified onshore currents at the crest of the nourishment. The increased wave breaking in the hybrid model contributes to these variations in flow velocity. Eddies are generated on both sides of the nourishment for both models, but the eddies are larger in the hybrid model, see Figure 35. These eddies create turbulence, which disturbs sediment transport and leads to the transfer of sediment into the sheltered area with less turbulence.

Similar to the wave height analysis, the flow velocities are plotted for the alongshore transect for both models under higher wave conditions ($H_{m0} = 3$m), see Figure 36. The shoreface nourishment is located approximately between alongshore distance x=9200 m and x=10800 m. By preventing the nourishment from flattening out excessively and thereby creating a more pronounced wave shadow zone, the hybrid model computes flow velocities in the lee of the nourishment that are approximately 30% lower compared to the standard model. Longshore velocities decrease gradually inside the lee of the nourishment; outside the shoreface nourishment, the velocities are higher for the hybrid model compared to the standard model, indicating larger eddies present at the tips of the nourishment.

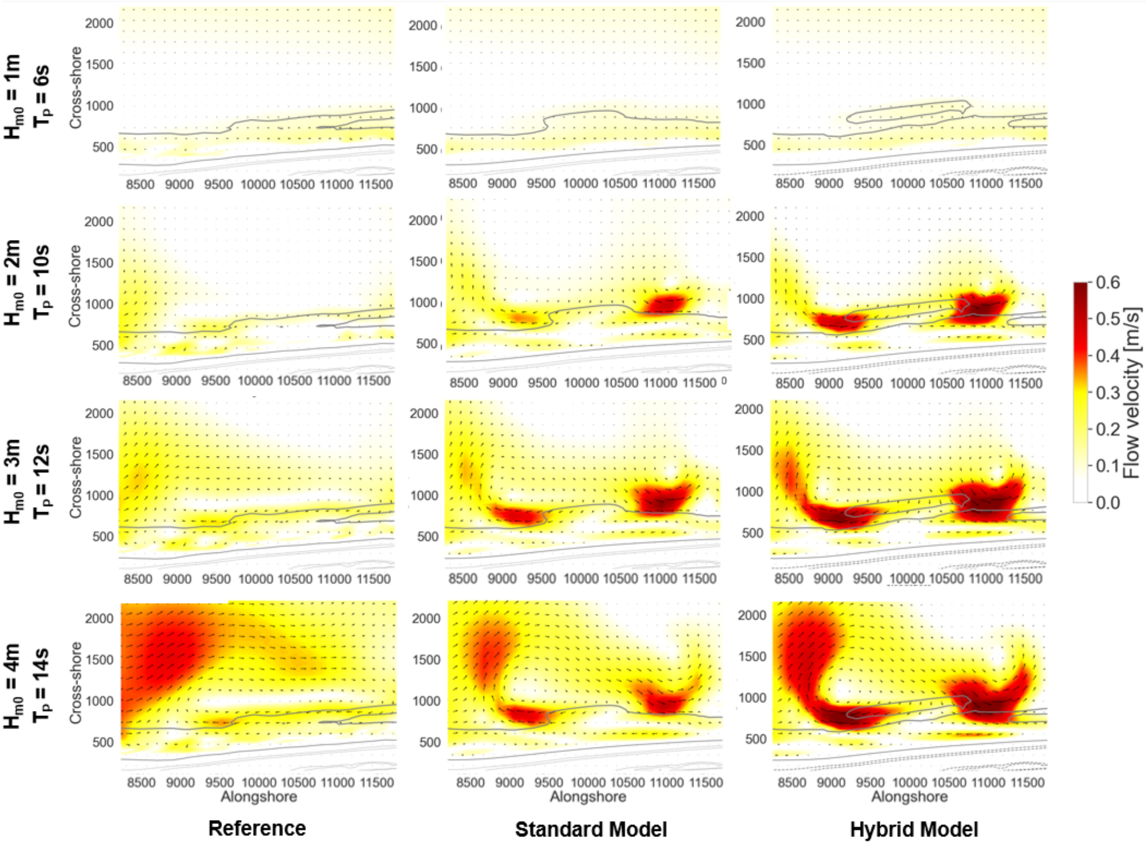


Figure 35: Flow velocities for waves coming from the north-west (315 degrees north, normally incident waves). Grey contourlines show the bathymetry.

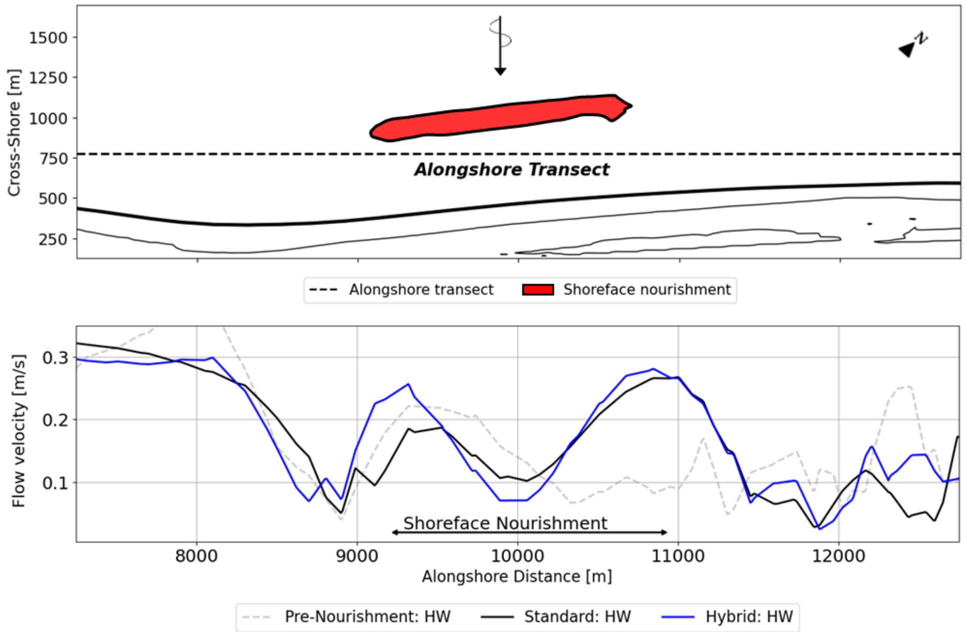


Figure 36: Flow velocity comparison along an alongshore transect under high (HW; H_{m0} = 3m) northwest (normally incident) wave conditions. The hybrid model shows 30% lower flow velocities in the central point of the lee of the nourishment, indicating a calmer wave climate compared to the standard model.

Additionally, the flow velocities are studied in case of oblique incident waves. The results are summarized in Apendix D (Section D.2). These oblique incident waves, approaching from the southwest, induce similar wave patterns to those created by normally incident waves, but with the shadow zone drifted slightly downdrift of the nourishment, see Figure 52 (Apendix D). Eddies, which are present on both lateral sides during normally incident waves, now appear only at the updrift as these rip currents are influenced by the alongshore current.

For oblique incident waves, the hybrid model computes flow velocities in the lee of the nourishment that are approximately 25% lower at the alongshore transect compared to the standard model, see Figure 53 (Apendix D), again demonstrating a more pronounced lee effect.

5.3.3 *Lee effect*

As a result of incorporating realistic cross-shore evolution of the nourishment, and thereby preventing the nourishment from flattening out excessively, the short-term one-day simulations reveal:

- a decrease in wave height in the lee of the nourishment, resulting in a more pronounced wave shadow zone for the hybrid model compared to the standard model;
- a decrease in flow velocity in the lee of the nourishment for the hybrid model for both normally as obliquely incident waves, with larger eddies present at the tip of the nourishment, compared to the standard model.

These short one-day runs indicate that subtle differences occur between the hybrid model and standard model under mild to high wave conditions. The reduction in wave height and longshore flow velocity indicates that the hybrid model exhibits a more pronounced lee effect, which is especially evident during higher wave events. The lee function is a key aspect in the evolution of shoreface nourishment, as sediment supplied by longshore currents can settle in the lee of the nourishment. A decrease in flow velocity in the lee can therefore lead to more sedimentation in this zone.

5.3.3.1 *Long-term simulations*

To further investigate the impact of a more pronounced lee effect, the representation of the lee effect is investigated based on longer-term runs of three months, in contrast to the short-term one-day

simulations discussed earlier in this section.
Results show that over a period of three months, the hybrid model computes a more pronounced wave shadow zone compared to the standard model, see Figure 37a. This figure shows the difference in wave height averaged over the five largest wave events across the simulation, with the hybrid model forecasting lower wave heights in the lee of the nourishment compared to the standard model, which is consistent with the observations from the short-term one-day runs in Section 5.3.1.

Interestingly, the areas with increased wave sheltering near the coastline, indicated by red boxes in Figure 37a, correspond to areas with increased sedimentation observed within the same red boxes depicted in Figure 37b. The intensified wave sheltering in the hybrid model leads to an increased interception of flow velocities, causing more sediment supplied by longshore currents to settle in the lee of the nourishment. This leads to more sedimentation in the lee of the nourishment compared to the standard model, resulting in a more pronounced lee effect.

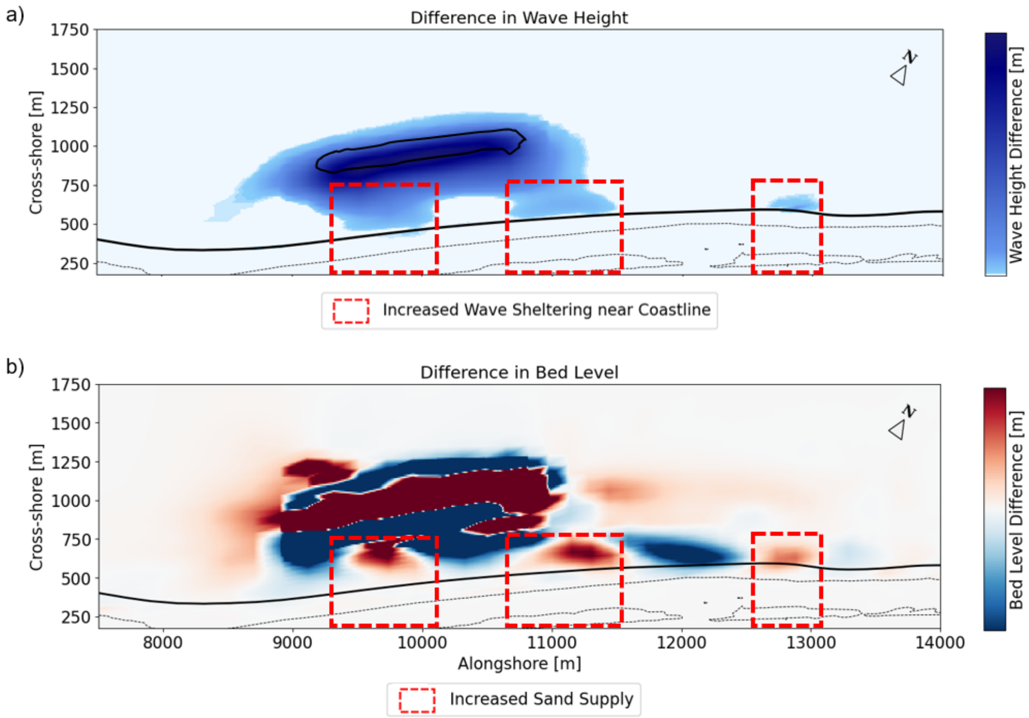


Figure 37: Lee effect comparison between hybrid model and standard model. (a) depicts the difference in wave height between the hybrid model and the standard model, in which the red boxes highlight increased wave sheltering at the coastline. (b) illustrates the difference in sedimentation and erosion. Increased sediment supply in the red boxes is observed, caused by increased wave sheltering in these zones.

To illustrate the mechanism by which the hybrid model exhibits a more pronounced lee effect, a conceptual model is presented in Figure 38. The hybrid model's ability to provide a more pronounced representation of the lee effect compared to the standard model can be explained in three steps:

1. By preventing the nourishment from flattening out excessively, the hybrid model shows greater wave breaking compared to the standard model, leading to a more pronounced wave shadow zone;

2. As a result of increased wave sheltering, the flow velocity in the lee of the nourishment reduces;

3. The reduction in flow velocity causes more sediment supplied by longshore currents to settle in the lee of the nourishment, promoting sedimentation in the lee of the nourishment for the hybrid model compared to the standard model.

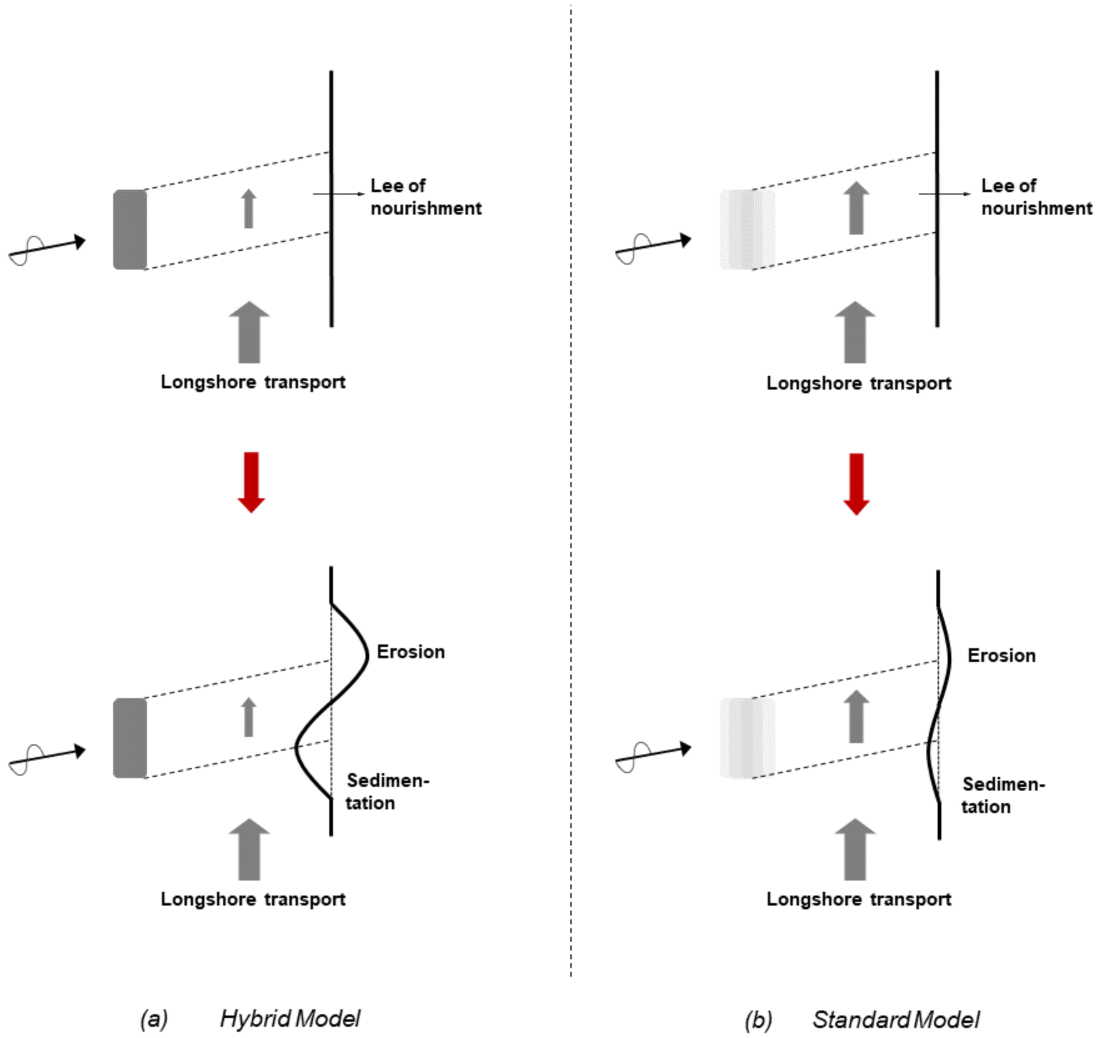


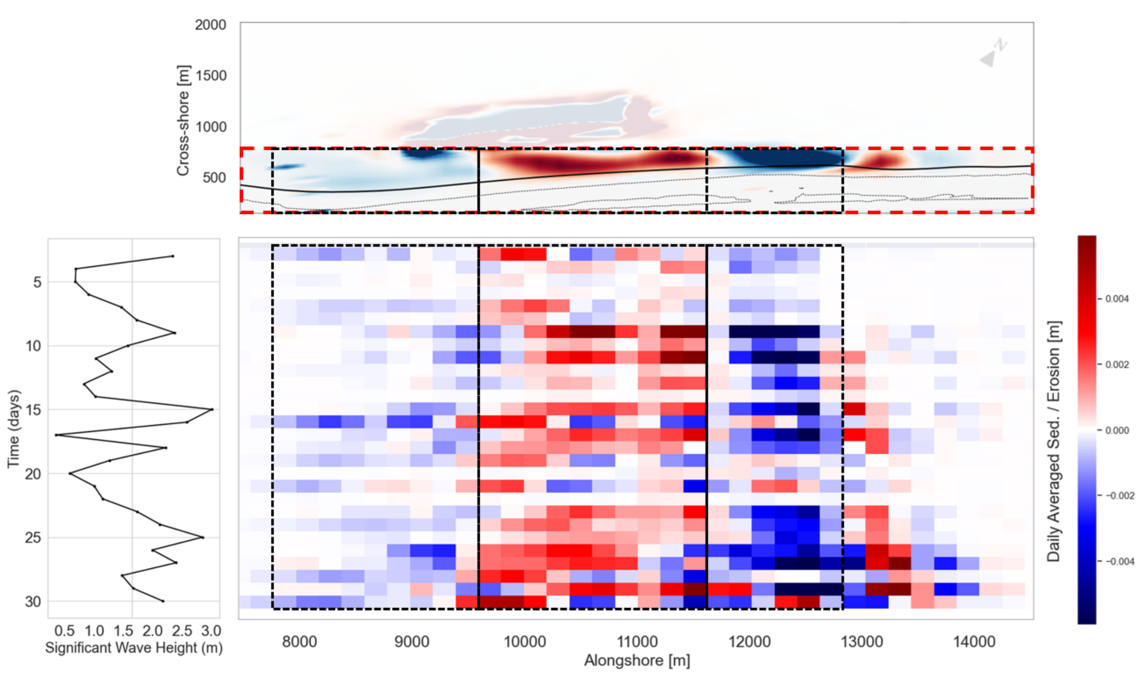
Figure 38: Conceptualization of the more pronounced lee effect in the hybrid model: 1) The hybrid model maintains its nourishment shape, whereas the standard model shows excessive diffusion. 2) This leads to enhanced wave sheltering in the hybrid model. 3) Enhanced wave sheltering results in greater longshore sediment reduction and more deposition. 4) Consequently, the hybrid model experiences increased sedimentation and erosion.

5.3.4 *Timestack of bed level changes*

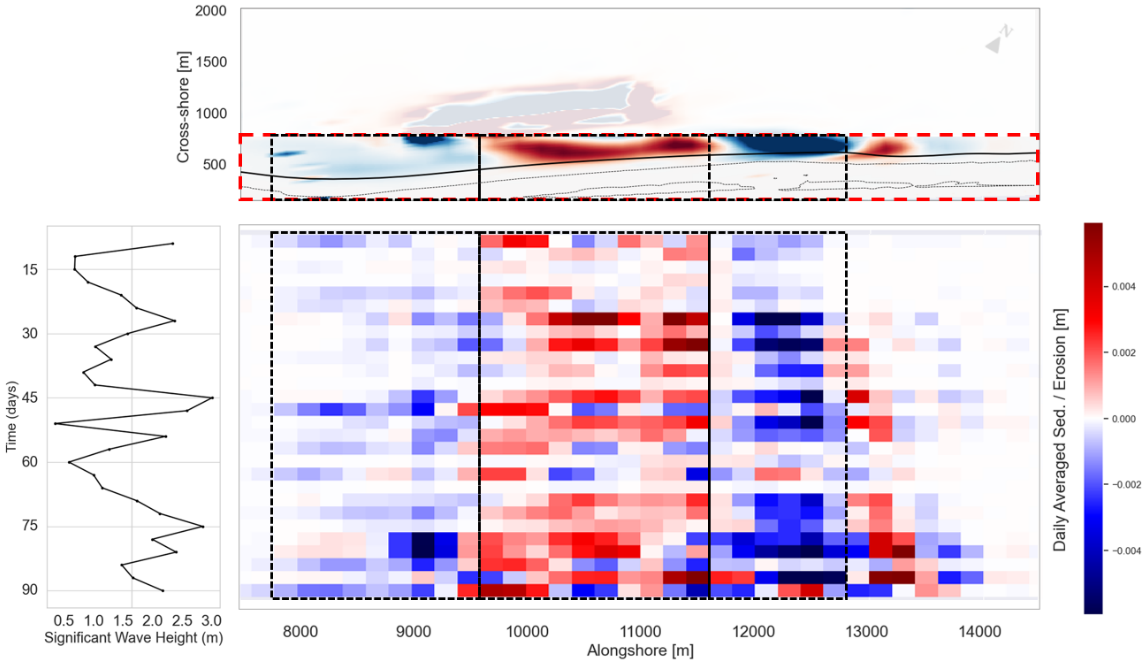
To better understand the added value of the hybrid model incorporating a more realistic lee effect, the spatio-temporal bed level changes in the nourishment area are studied. The cross-shore averaged bed level changes are presented as a timestack, see Figure 39. The figure presents the daily bed level changes averaged across the cross-section along the nourishment area outlined by the red box presented in the upper panel of the figure.

The lee of the nourishment, ranging from approximately x=8000 m to x=9400 m, is subject to almost continuous sedimentation for both the hybrid model as the standard model, intensified during the higher wave events, see left panel of Figure 39. Additionally, updrift of the nourishment (ranging from approximately x=8000 m to x=9400 m) continuous erosion occurs for both models. Downdrift, from approximately x=11500 m to x=12750 m, there is also continuous erosion for both models. A small spot of sedimentation is noticeable from x=12750 m to x=13250 m, potentially resulting from the erosion occurring updrift.

Moreover, the magnitude of sedimentation appears to intensify during periods with larger waves, as illustrated in the left panel of the figures: larger daily cross-shore averaged bed level changes tend to coincide with higher wave events, and vice versa.



((a)) Timestack for standard model



((b)) Timestack for hybrid model

Figure 39: Time-stack of daily volume changes averaged over the cross-section for (a) standard model, and (b) the hybrid model. Blue patches indicate erosion; red indicates sedimentation. The left panel shows daily-averaged wave heights. For both models, continuous sedimentation in the lee of the nourishment can be observed, with continuous erosion updrift and downdrift of it, depicted by the three black boxes. The magnitude of sedimentation / erosion appears to be intensified during higher wave events.

5.3.4.1 *Added value of a hybrid model*

The difference in daily cross-shore averaged bed level changes between the hybrid model and standard model, presented again as a timestack in Figure 40, shows that the difference in daily bed level changes between the models increases over time. A similar trend was observed in Section 5.2.5. The right panel illustrates the evolution of the maximum crest height at the center of the nourishment, which is used to illustrate the rate of nourishment flattening. The crest rapidly decreases in the standard model (from -4.2 m + NAP initially to -4.8 m + NAP in the end), while the hybrid model shows a slight increase in maximum crest height. This growing difference leads to a corresponding increase in computed difference in daily bed level changes between the models, see Figure 40. Initially, the difference in crest height between the models is minimal, causing waves to break similarly over the nourishment in both. However, as time progresses and the crest height difference increases, waves that break in the hybrid model will not break in the standard model due to its excessively flattened nourishment shape. As a result, the hybrid model computes a calmer wave climate with smaller flow velocities in the lee of the nourishment, reducing the transport capacity and thus trapping sand in the lee at an increased rate.

Additionally, increased daily bed level differences are observed during larger wave events. During these events, the hybrid model exhibits a more pronounced lee effect compared to the standard model, suggesting that the hybrid model exhibits a stronger lee effect under such wave conditions, forcing waves to break earlier and/or more frequently.

Futhermore, a steady volume is supplied to the areas outlined by the black boxes, see Figure 40. This indicates that sediment deposition in these areas is not solely attributed to a single wave event but rather the cumulative effect of multiple events over time. Despite waves varying in direction, the sand consistently accumulates in the sedimentation areas marked by the black boxes, intensified during four to five wave events during which the enhanced lee effect becomes even more significant.

These observations, along with the findings presented in Section 5.2.5, highlight the added value of the hybrid model, which is attributed to an enhanced representation of the lee effect:

- The added value of the hybrid model increases over time as the lee effect becomes increasingly more pronounced compared to standard models that flatten excessively;
- The hybrid model's added value is especially significant during larger wave events when the lee effect plays an important role.

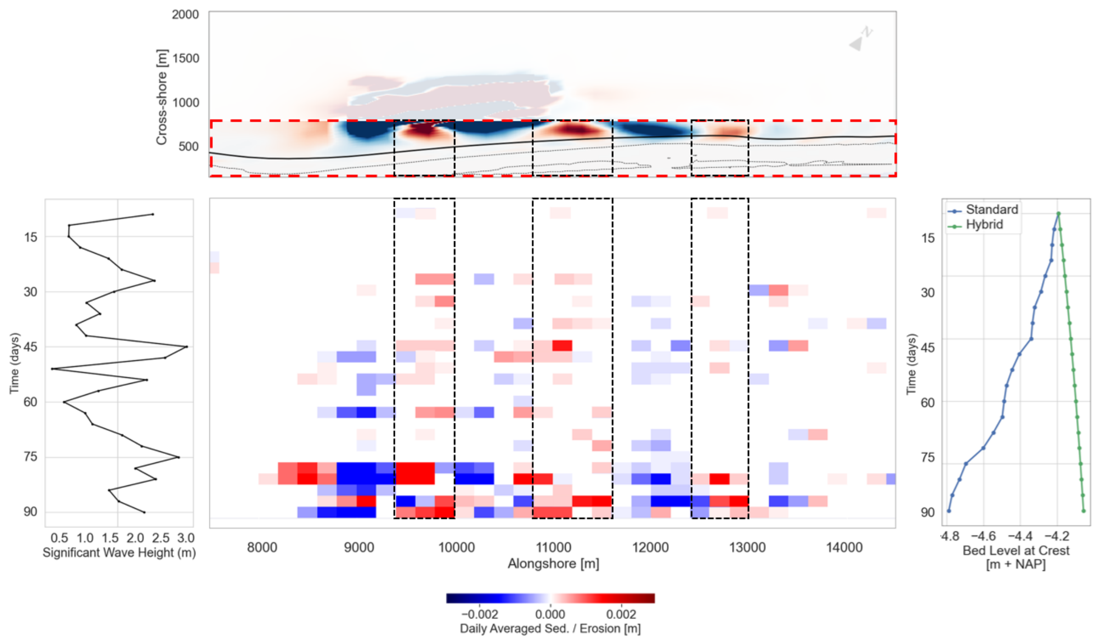


Figure 40: Timestack of difference (hybrid - standard) in daily cross-shore averaged bed level changes between the models. Blue patches indicate erosion; red indicates sedimentation. The left panel shows the corresponding wave heights; the right panel the evolution of the maximum crest height at the center of the nourishment.

5.4 FLATTENING CONDITIONS

Figure 39 and Figure 40 both indicate that the magnitude of sedimentation and erosion patterns vary in response to wave intensity. Therefore, this sections elaborates on the forcing conditions that are likely to cause the excessive flattening as observed in standard Delft3D-FM models, aiming to find dependencies between the artificial flattening in Delft3D-FM and the forcing conditions.

5.4.1 *Erosion due to wave events*

The artificial flattening of the nourishment as modelled with the standard model is not a smooth process: the vertical displacement of the nourishment crest, Δz, fluctuates over time and is primarily governed by the wave height, see Figure 41 and Figure 42.

To explore the dependencies between the flattening of the nourishment crest and the forcing conditions, the vertical displacement is plotted against the wave height and bed shear stress. The nourishment crest exhibits faster flattening with increasing wave heights. For wave heights above 1.0 m, increased flattening is observed, indicated by grey boxes in the upper and middle panels in Figure 41. Contrary, almost no flattening is observed for for wave heights smaller than 1.0 m, as it shows near zero vertical displacement for $H_s < 1.0$m. However, vertical displacement increases significantly for waves exceeding 1m.

Furthermore, a reduction in the magnitude over time is observed. For example, at day 8, a wave height of 2.25m resulted in larger vertical displacement compared to a wave height of 3.0m at day 29. This suggests that as the nourishment flattens out, the vertical displacement gradually decreases as it approaches its equilibrium.

Additionally, the influence of the tide on the artificial flattening is examined by plotting bed shear stress against vertical displacement, considering that tides can influence the bed shear stress at the crest. Tides can affect bed shear stress at the crest, potentially influencing the process of flattening. However, model results indicate that bed shear stress largely correlates with wave height, suggesting that flattening is primarily governed by incoming wave characteristics rather than tidal influence.

Figure 41: Artificial flattening of nourishment crest as modeled with the standard model. Vertical displacement of the nourishment crest, Δz, is primarily driven by wave height, revealing faster flattening with increasing wave heights. Minimal flattening is observed for wave heights below 1.0m, while significant displacement occurs for waves exceeding 1m in height. A gradual reduction in magnitude over time suggests approaching equilibrium. Although tide-induced flow variation may influence erosion slightly, model results indicate wave height predominantly governs flattening.

5.4.1.1 *Correlation between flattening and forcing conditions*

Figure 41 indicates that artificial flattening of the nourishment is primarily governed by wave height. To further investigate this relation, the correlation between the vertical displacement (Δz) and wave height is examined. The correlation coefficient is 0.75 (Figure 42a), indicating a strong correlation between the two. This implies that as wave height increases, there is a clear tendency for vertical displacement to also increase.

Similarly, a correlation coefficient of 0.82 is found for the bed shear stress, which is influenced not only by the wave height but also by the tidal flow over the nourishment crest. However, the correlation coefficient of the bed shear stress is only slightly higher than for the wave height, suggesting that wave height remain the dominant factor governing the flattening process.

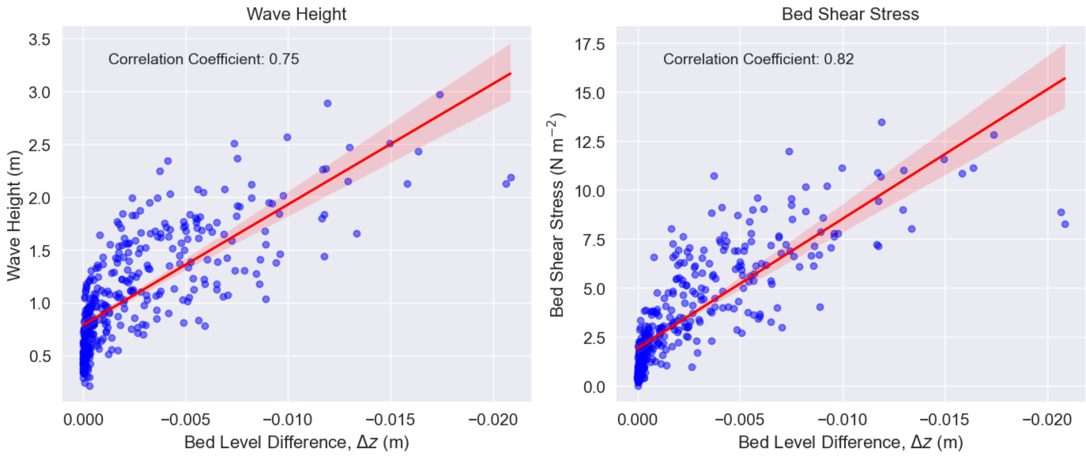


Figure 42: Correlation between vertical displacement and wave height as well as vertical displacement and bed shear stress. (a) A correlation coefficient of 0.75 between vertical displacement (Δz) and wave height confirms a strong positive relationship, indicating increased displacement with higher wave heights. (b) Bed shear stress, also influenced by tidal flow, shows a slightly higher correlation coefficient of 0.82, validating wave height as the dominant factor.

5.4.2 *Flattening: bed load vs suspended load driven*

To further explore which sediment transport mechanism specifically drives the flattening of the nourishment, the contributions of bed load and suspended load transport in sediment transport are examined (Figure 43). This aims to identify the dominant transport process responsible for the bed level changes at the crest of the nourishment.

Overall, the bed load transport seems the more slightly more pronounced compared to suspended load transport. However, three peaks can be observed in the suspended load transport, where it exceeds bed load transport significantly. This suggests that while bed load transport may play a more pronounced overall role in shaping the bed profile, there are specific instances where suspended load transport dominates.

Figure 43: Comparison of bed load and suspended load transport contributions in sediment transport, aiming to identify the dominant mechanism driving the flattening of the nourishment. While bed load transport appears slightly more pronounced overall, three distinct peaks in suspended load transport suggest instances where it significantly exceeds bed load transport.

6 DISCUSSION

6.1 MAIN FINDINGS

Accurately predicting shoreface nourishment behavior is challenging due to excessive flattening of the cross-shore profile in current morphological process-based models like Delft3D-FM. In order to address this issue, a hybrid model has been developed that seamlessly integrates a data-driven component into Delft3D-FM. The presented model framework prevents the nourishment from flattening out excessively by enabling user-defined manipulation of bed level changes during simulation through Basic Model Interface. In a case study at the coast of Ter Heijde, the model was able to reproduce the Ter Heijde '97 shoreface nourishment without excessive flattening, thereby demonstrating the model's proof-of-concept.

The hybrid model has shown promise for more accurately representing the lee effect of a shoreface nourishment. Compared to the standard model, there was a decrease of wave height and flow velocity just shoreward of the nourishment, resulting in a more significant lee effect that influences the alongshore redistribution of the deposited nourishment sediment. According to the model results, inaccuracies in cross-shore modelling have the potential to also affect the accuracy of longshore morphological predictions. The differences in sedimentation / erosion patterns in longshore direction between the hybrid model and the standard model, attributed to the nourishment volume only, are between 10-25% after three months of morphological modelling, a difference that is expected to increase over time based on a trend of growing divergence found between the models.

The most significant contributions to the current state of shoreface nourishment modelling are summarized below:

- The hybrid model demonstrates proof-of-concept. In a case study at Ter Heijde, the model successfully reproduced the Ter Heijde '97 shoreface nourishment without excessive flattening. The model framework allows user-defined manipulation of bed level changes during simulation through Basic Model Interface, thereby steering the nourishment's cross-shore evolution and preventing excessive flattening of the nourishment.

- The hybrid model shows potential for more accurately representing the lee effect of a nourishment. By preventing excessively flattening of the nourishment, a reduction in wave height and flow velocity is observed in the lee of the nourishment, leading to increased sedimentation compared to the standard model.

- Incorporating accurate cross-shore modelling to better represent the lee effect provides added value for assessing longshore morphological changes. Inaccuracies in cross-shore modeling, as observed in standard models, have the potential to significantly impact longshore predictions over time.

Although the development of the hybrid modelling framework has contributed to a better understanding of shoreface nourishment modelling, it still has significant limitations. For a detailed description of these limitations, see Section 6.2.

6.1.1 *Implications of findings*

This subsection discusses the implications of the findings of this thesis, comparing them with current modeling capabilities and placing them in the context of future research opportunities.

6.1.1.1 *State of present-day shoreface nourishment modelling in Delft3D-FM*

As a result of conducting a case study, we confirm that standard models still show excessive flattening of the cross-shore profile, meaning that the conclusion as drawn in previous studies (Giardino et al., 2010; Grunnet et al., 2004; Van Duin et al., 2004) conducted many years ago is still relevant (Chapter 3).

The computed flattening within Delft3D-FM is not a smooth process as the vertical displacement of the nourishment crest varies over time. This vertical displacement shows dependencies on forcing conditions, primarily driven by the larger wave events (Chapter 5). This observation provides insights for future research directions, for example by weighting the maximum allowable vertical displacement per timestep in Delft3D-FM with wave height, or implement controls to 'pause' morphological changes during those wave events.

6.1.1.2 *Integration of a data-driven component into Delft3D-FM*

This thesis has led to the development of a model framework that integrates a data-driven component into the process-based Delft3D-FM trough BMI (Chapter 4). This framework facilitates the exchange of variables during its simulation, enabling the monitoring and steering of bed level changes in Delft3D-FM according to user-defined parameters.

This framework holds potential to be used for future research. The seamless communication accomplished by this framework can be seen as lifting the hood of a car, revealing a new range of opportunities for in-depth analysis of current shortcomings and potential enhancements to Delft3D-FM by having the ability to take a real-time glimpse into the internal components of the model's engine. We anticipate this thesis to be a starting point for more sophisticated ways to incorporate accurate cross-shore evolution trough this model framework, given that limitations outlined in the next section are addressed.

6.1.1.3 *Implications of inaccurate cross-shore modelling on longshore predictions*

This study underlines the importance of cross-shore modelling for longshore morphological predictions. As discussed in Chapter 5, differences in sedimentation / erosion patterns were observed between the hybrid model and standard model, attributed to the difference in wave sheltering between the models. The hybrid model demonstrates the potential for more accurately representing the lee effect of shoreface nourishments by preventing excessive flattening of the nourishment. Results show a more pronounced wave sheltering effect. According to the findings, this leads to differences ranging from 10-25% in the alongshore redistribution of nourishment sediment across distinct longshore areas between the models.

Furthermore, it was found that the difference between the hybrid model and standard model increases over time. This divergence is attributed to rapid flattening of the nourishment observed in the standard model, while hybrid model does not show excessive flattening and aligns with observations. Consequently, the difference between the models is expected to increase over time.

These findings suggest that cross-shore inaccuracies likely have a significant impact on longshore predictions as well. Results show that after almost three months of morphological modelling, the cross-shore profile is almost completely flattened out in the standard model, resulting in negligible lee effect from this moment onwards. In contrast, observations show the preservation of the nourishment shape for 3-4 years. This implies that, for example, after three years, the hybrid model continues to calculate the lee effects in its simulation, while the standard model has already completely diffused for almost 2.5 years. Model results will keep diverging as time progresses, underlining the importance of preventing the nourishment from flattening excessively.

This indicates that completely separating cross-shore effects from longshore effects, as seen in most numerical models to date, is accompanied with inaccuracies in longshore predictions.

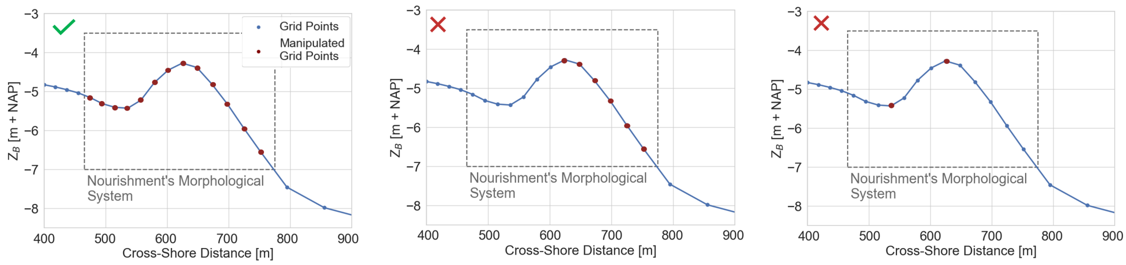
6.2 LIMITATIONS

For the data-driven manipulation of the bed level at the nourished area, various methods were tested to make a first step towards predicting shoreface nourishment evolution (i.e. crest-trough method and slope manipulation method; Appendix C). However, during the evaluation of these methods revealed manipulation constraints, as manipulation of the bed level was found to only be successful when applied over the entire nourishment area, rather than targeting selective parts (e.g. the crest and trough). Furthermore, another significant limitation is the computational effort needed to run the hybrid model. A more detailed analysis of these limitations, and suggestions to overcome them, is provided in the subsection below.

6.2.1 *Manipulation constraints*

The hybrid model is subject to manipulation constraints as manipulating the bed level in Delft3D-FM trough BMI is found to only be successful if applied across the entire profile of the shoreface nourishment. If manipulation is limited to selective parts of the nourishment area (e.g., only the crest and/or trough, or solely the seaward slope; see Figure 44), the model shows poor results, see Appendix C.

A potential explanation for the poor results in these selective manipulation methods (e.g. crest-trough method and slope manipulation method) is that altering the bed level only at specific points diverges too much from the model's intrinsic behavior. Such manipulation fails to align with the overall sediment transport transport within the model, where the sediment transport field appears to hold dominance. Delft3D-FM operates in two half-timesteps, with hydrodynamics and sediment transport calculated initially. In the subsequent half-timestep, gradients in sediment transport leads to sedimentation or erosion in grid cells. In this half-timestep, a bed level level is imposed based on the data-driven manipulation, which may not be consistent with the calculated sediment transport if done only for selective parts of the nourishment area. Selective manipulation within the nourishment area proves problematic, as it disrupts the overall mass conservation within the morphological system. A shoreface nourishment can be seen as a morphological system consisting of a crest and trough, which together are approximately mass conservative overall. If only a selective part of this system is manipulated, e.g. the crest, the sediment transport field in Delft3D-FM will still result in the trough being calculated based on this overall sediment transport field, causing the trough's bed level update to be influenced by the gradients of this transport field rather than localized manipulation. It seems that the dominance of the transport field hinders the model's ability to interpret manipulated bed levels effectively for sediment transport calculations if done only for selective parts of a morphological system.



((a)) Full manipulation

((b)) Selective manipulation: slope manipulation

((c)) Selective manipulation: crest-trough method

Figure 44: Data-driven manipulation methods. (a) shows the full reproduction of the nourishment, (b) and (c) show selective manipulation methods, the slope manipulation method and crest-trough method, respectively, which showed poor results.

6.2.1.1 *Suggestions to overcome manipulation constraints*

To address manipulation constraints, two suggestions are proposed for future research in predicting shoreface nourishments evolution trough a data-driven approach.

The first suggestion is to explore ways to manipulate the bed level across the entire nourishment area. This entails full manipulation of the nourishment area, including the development of both the crest and the trough, rather than selective manipulation.

The second suggestion proposes a different approach to nourishment manipulation. In stead of directly manipulating the bed level, this approach proposes intervening one step earlier in the morphodynamic feedback loop utilized in Delft3D-FM by manipulating sediment transport gradients leading to the desired bed level.

Since the transport field seems to be inconsistent with the bed level update in selective manipulation methods, leading to poor results, adjusting gradients in sediment transport to match the desired bed level evolution can be an interesting topic for future research. As bed level changes are governed by the formula $(1-p)\frac{\partial z_b}{\partial t} + \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} = 0$, one can achieve the desired bed level change, dz_b, over a timestep by manipulating the sediment transport gradients, $\frac{\partial S_x}{\partial x}$ and $\frac{\partial S_y}{\partial y}$, to match the desired bed level change. This process requires determining a ratio, α, between the two sediment transport gradients, which can potentially be derived based on the dominance of cross-shore transport (60-85%) over longshore transport in shoreface nourishments. With this ratio, the equation becomes $\frac{\partial z}{\partial t} + \frac{\alpha}{\partial y}\frac{\partial S_y}{\partial y}\frac{\partial x}{\partial S_x} + \frac{\partial y}{\partial S_y} = 0$, which can be solved. To determine the feasibility of this approach, a deeper understanding of the ratio between $\frac{\partial S_x}{\partial x}$ and $\frac{\partial S_y}{\partial y}$ is necessary. Additionally, the involvement in bed load and suspended load in nourishment evolution must be conducted to determine which transport mechanism is dominant. Bed load transport offers more convenient opportunities, as it is represented simply as a vector in Delft3D-FM and can thus be more easily manipulated, while suspended load is depended on the sediment concentration profile and flow velocity over the water column, making manipulation more difficult.

6.2.2 *Computational effort*

Additionally, the computational effort required for monitoring and steering bed level changes in Delft3D-FM through a data-driven controller in BMI is significantly higher compared to standard Delft3D-FM models without manipulation, see Section D.1. Continuous or frequent data exchange in the modelling framework, manipulating the bed level in each timestep, leads to significant computational costs due to the overhead associated with model input/output. The computational demand required of the model increases with the amount of anchor points used: full manipulation (twenty anchor points per cross-shore transect) takes more time than the crest-trough method (two anchor points per cross-shore transect).

6.2.2.1 *Suggestions to overcome computational heaviness*

The increase in computational heaviness is a significant limitation to the model. In order to make the prediction of shoreface nourishments possible trough this method, this limitation needs to be overcome. Suggestions to achieve this are summarized below.

- Minimal anchor points. Computational heaviness increases with the amount of anchor points used. An optimal solution requires as minimal anchor points as possible to decrease computational efforts.
- Decrease manipulation frequency. Currently the bed level is manipulated every user timestep in Delft3D-FM. A potential way to decrease computational overhead is to decrease the frequency of bed level manipulation. Currently, bed level manipulation occurs for every user timestep in Delft3D-FM. A potential solution is to decrease the frequency of manipulation, such as only manipulating the timestep just before SWAN starts updating its wave field (which means manipulating approximately 1 in 12 timesteps, instead of all 12 out of 12 timesteps that occur in one SWAN update).
- Using filtered and compressed time series, instead compressed only. Filtering out wave heights lower than 1.0m from the time series may lead to more efficient use of the simulation time. Wave events below 1.0 m barely contribute to flattening of the nourishment (Chapter 5)
- Higher morphological acceleration factor (*morfac*). A higher *morfac* may increase computational efficiency.

7 CONCLUSIONS

In the last decades, an increasing number of shoreface nourishments have been implemented along the Dutch coast to mitigate coastal erosion. Designing effective shoreface nourishments requires a comprehensive understanding of their complex morphological evolution. However, accurately predicting this evolution using morphological process-based numerical models like Delft3D-FM poses significant challenges. Delft3D-FM models experience excessive artificial flattening of the nourishment, resulting in an inaccurate representation of the cross-shore profile. The implications of this inaccuracy on longshore morphological predictions were previously unclear.

The main goal of this thesis is to make a contribution towards incorporating more accurate cross-shore evolution of shoreface nourishments. To achieve this, a proof-of-concept is demonstrated for a hybrid model that seamlessly incorporates a data-driven component into the process-based numerical model Delft3D-FM through Basic Model Interface (BMI). The hybrid model prevents excessive flattening of the nourishment by enabling user-defined manipulation of bed level changes during simulation, thereby steering the nourishment's cross-shore evolution.

Furthermore, this study contributes to a better understanding of the added value of a model that incorporates more realistic cross-shore evolution of shoreface nourishments. First, the extent and causes of excessive cross-shore flattening in present-day Delft3D-FM models is evaluated by means of a case study. Second, the seamless modelling framework of the hybrid model is developed, which is then applied to replicate a shoreface nourishment at the coast of Ter Heijde, demonstrating the proof-of-concept and allowing for a comparison between the hybrid model and the standard, standalone Delft3D-FM model.

The findings show that a hybrid model approach more accurately represents the nourishment's lee effect, which plays an important role in the morphological response to a shoreface nourishment. The hybrid model prevents excessive flattening of the nourishment, leading to a reduction in wave height and flow velocity in the lee of the nourishment compared to the standard model. This results in greater sedimentation shoreward of the nourishment. The difference between the models is expected to increase over time as the hybrid model continues to exhibit its lee effect for years while the standard model is already completely diffused after a few months.

This indicates that accurately representing cross-shore evolution, leading to a more realistic representation of the lee effect, has the potential to also significantly impact longshore predictions over time. This information can help increase the understanding of the development of shoreface nourishments, and shows the added value of a model that more accurately represent cross-shore profile evolution.

Detailed conclusions of the three research questions (RQs) are provided below.

To what extent do present-day Delft3D-FM models show excessively flattening of the cross-shore profile, and is there a dependency on forcing conditions? *RQ1*

First, we evaluate the extent of excessive flattening in present-day Delft3D-FM models, which leads to an inaccurate representation of the cross-shore profile. While earlier studies on shoreface nourishments (Giardino et al., 2010; Grunnet et al., 2004; Van Duin et al., 2004) provided valuable insights on shortcomings of shoreface nourishment modelling in Delft3D-FM, their relevance is questionable as those studies are conducted nearly two decades ago. With the continuous developments and updates in Delft3D, including the introduction of Delft3D-FM and the capability to conduct brute-force simulations, it was investigated to what extent present-day models still experience excessive flattening of the cross-shore profile.

To address this research question, a case study of a shoreface nourishment at Ter Heijde is conducted. The model used utilizes Delft3D Flexible Mesh and capable of conducting brute force simulations. Despite incorporating highly realistic boundary conditions, and implementing a refined grid in the nourishment area, the standard model still shows excessive flattening of the cross-shore profile, resulting in unrealistic representations of the cross-shore evolution of shoreface nourishments in Delft3D-FM (see Chapter 3). Jarkus measurements from this case study showed both a landward migration and increase of crest height, along with the formation of a trough after one year. The Delft3D-FM model does not include these features, as the cross-shore profile is completely flattened out. Notably, the amount of sediment pickup at the most seaward side of the nourishment was modelled accurately, but the landward redistribution of this available sediment is represented poorly, which presents opportunities for integrating data-driven manipulation methods to steer the landward evolution of nourishments.

Furthermore, it was found that the observed artificial flattening within Delft3D-FM is not a smooth process as the vertical displacement of the nourishment crest varies over time. This vertical displacement shows dependencies on forcing conditions, primarily driven by the larger wave events with wave height $H_s > 1.0$ m. (Chapter 5).

RQ2 *Can the integration of a data-driven component into the process-based Delft3D-FM through Basic Model Interface mitigate excessive artificial flattening of shoreface nourishments?*

For this purpose, a hybrid model is presented that enables seamless and continuous monitoring and steering of the bed level in Delft3D-FM via a controller environment in BMI (Chapter 4). This method prevents the nourishment from flattening out excessively by enabling user-defined manipulation of bed level during its simulation. The hybrid model is then applied to reproduce the observed shoreface nourishment evolution at the coast of Ter Heijde during the first months of morphological changes.

The hybrid model has shown proof-of-concept for this case study (Chapter 5) by representing the behavioral characteristics of shoreface nourishment evolution outlined in Chapter 2: (1) landward shift and crest height increase (i.e. not rapidly diffusing), (2) milder seaward facing slope and (3) steeper landward facing slope and trough formation–characteristics absent in standard FM models.

However, it is important to note that manipulating the bed level in Delft3D-FM through BMI is found to only be successful if we manipulate over the entire profile of the shoreface nourishments. If only parts of the system are manipulated (e.g. only the crest and trough, or only the seaward slope, see Appendix C), the hybrid model shows unrealistic results. Furthermore, the computational effort required to run to hybrid model is significantly larger than standard models. In order to enable prediction of shoreface nourishment evolution with a hybrid model approach, these limitations need to be overcome.

RQ3 *What are the implications of inaccurate cross-shore modelling on longshore morphological predictions in the context of shoreface nourishments?*

For this objective, the hybrid model is applied to the coast of Ter Heijde for which a shoreface nourishment is reproduced according to Jarkus measurements. By preventing excessive flattening observed in standard models and steering the evolution to align with observed behavior, any difference between the hybrid model and the standard model provided insights into the implications of inaccuracies in the cross-shore evolution on longshore predictions.

Thy hybrid model shows a more pronounced wave sheltering effect compared to the standard model as the nourishment is prevented from flattening out rapidly, enabling the ongoing representation of the lee effect of the nourishment. Waves break earlier and/or more frequently in the hybrid model, causing a calmer wave climate in the lee of the nourishment compared to the standard model. As a result, the flow velocity in the lee reduces which causes sediment supplied supplied by longshore currents to settle at a higher rate compared to the standard model, leading to increased sedimentation in the nourishment's lee. After three months of morphological modelling, the difference in sedimentation attributed to the nourishment volume in these areas shows a difference of 10 - 25 % between the models. The difference in wave sheltering in turn also leads to calculated differences in the adjacent areas experiencing erosion.

Overall, the results demonstrate a difference in longshore prediction between the hybrid model and standard model. This implies that manipulating the cross-shore evolution of shoreface nourishment, leading to a more realistic representation of the lee effect, also affects longshore predictions. Furthermore, a trend is observed in the difference between the models: the difference seems to increase over time. This growing divergence between the models suggests that inaccurately representing the cross-shore evolution of shoreface nourishments has the potential to cause significant inaccuracies in longshore direction over time, and that accurate cross-shore modelling leading to a more realistic representation of the lee effect, should not be ignored when assessing longshore morphological changes in the context of shoreface nourishments.

8 RECOMMENDATIONS

Based on the limitations outlined in Chapter 6, and the conclusions outlined in Chapter 7, this chapter provides an overview of recommendations for future research regarding a hybrid model approach, integrating a data-driven approach to Delft3D-FM.

The recommendations are summarized below, prioritized from top to bottom:

- Enable longer-term simulations to validate the hypothesis that the hybrid model provides an increased and sustained added value over time.
- Reduce computational effort required to run the hybrid model. Suggestions to achieve this are:
  - Decrease manipulation frequency. Manipulate the bed level only before significant updates, like SWAN wave field updates, instead of at every timestep to enhance computational efficiency.
  - Minimize amount of anchor points. Optimize the number of anchor points used for bed level manipulation to reduce computational demand, ensuring accurate results without unnecessary overhead.
  - Use filtered and compressed time series. Filter out wave events below a certain threshold (e.g., 1.0 m) to improve simulation efficiency and achieve longer simulation duration.
- Manipulation through gradients in sediment transport: investigate manipulating sediment transport gradients instead of directly altering bed levels, which showed limitations. This approach could align the desired bed level evolution with the overall sediment transport field in the model. An additional benefit of manipulating by sediment transport gradient instead of directly manipulating the bed level is that it inherently ensures mass conservation, as bed level evolution by sediment transport gradients takes sediment from one place in the system to another, thus eliminating concerns related to mass conservation.
- Use the developed seamless modelling framework for:
  - Integration of a cross-shore oriented numerical model. Coupling Delft3D-FM with a 1D stand-alone numerical model that specially focuses on modelling the cross-shore evolution. This cross-shore oriented model can then be used to overwrite Delft3D-FM's cross-shore evolution.
  - Integration of Machine Learning: use machine learning (ML) to ensure accurate cross-shore evolution of the nourishment. Train a ML model on shoreface nourishment evolution along the Dutch coast using Jarkus surveys, which are annual bathymetry surveys. The ML model can be trained with data from each yearly measurement to predict the subsequent year's bathymetry. Consequently, a single shoreface nourishment with a lifespan of 4-5 years provides 4-5 training sets. With numerous shoreface nourishments measured along the Dutch coast, this results in an extensive dataset for training the ML model in predicting cross-shore evolution. This ML model can then be used overwrite Delft3D-FM's cross-shore evolution.

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A

DELFT3D FLEXIBLE MESH SUITE

In this thesis Delft3D Flexible Mesh (FM) is used to simulate hydrodynamics, sediment transport and morphology (Deltares, 2023). Delft3D-FM is the successor of Delft3D (Lesser et al., 2004), and is compatible with Basic Model Interface.

Delft3D-FM consists of coupled modules that collectively enable the simulation of various processes, such as hydrodynamic flow (based on shallow water equations), sediment transport and morphological changes (Lesser et al., 2004).

At the core of Delft3D lies the FLOW module, responsible for hydrodynamic calculations by solving the two (depth-averaged) or 3D shallow water equations (Lesser et al., 2004). These equations are summarized below. Delft3D-FLOW operates together with Delft3D-WAVE, which is used to compute wave propagation. Every the coupling time step, DELFT3D-FLOW supplies DELFT3D-WAVE with a new flow field, including water levels and depth-averaged currents. The next step is calculating the bed level change by using the Delft3D-SED module, which computes sediment transport and morphodynamic evolution due to the combined effect of flow and waves.

The horizontal momentum equations and continuity equation used for the FLOW module are summarized below.

Horizontal momentum equations:

$$\frac{\partial \mathbf{U}}{\partial t} + U\frac{\partial \mathbf{U}}{\partial x} + v\frac{\partial \mathbf{U}}{\partial y} + \frac{\omega}{h}\frac{\partial \mathbf{U}}{\partial \sigma} - fV = -\frac{1}{\rho_0}P_x + F_x + M_x + \frac{1}{h^2}\frac{\partial}{\partial \sigma}(\nu_v \frac{\partial u}{\partial \sigma}) \tag{1}$$

$$\frac{\partial \mathbf{V}}{\partial t} + U\frac{\partial \mathbf{V}}{\partial x} + V\frac{\partial \mathbf{V}}{\partial y} + \frac{\omega}{h}\frac{\partial \mathbf{V}}{\partial \sigma} - fU = -\frac{1}{\rho_0}P_y + F_y + M_y + \frac{1}{h^2}\frac{\partial}{\partial \sigma}(\nu_v \frac{\partial v}{\partial \sigma}) \tag{2}$$

Continuity equation:

$$\frac{\partial \xi}{\partial t} + \frac{[\partial h\overline{U}]}{\partial x} + \frac{[\partial h\overline{V}]}{\partial x} = S \tag{3}$$

Where:

- **U**: Horizontal velocity component in the x-direction
- **V**: Horizontal velocity component in the y-direction
- ω: Vertical vorticity
- h: Water depth or fluid thickness
- σ: Vertical coordinate
- f: Coriolis parameter

- ρ_0: Reference density of the fluid
- P_x: Pressure gradient in the x-direction
- P_y: Pressure gradient in the y-direction
- F_x: External force in the x-direction
- F_y: External force in the y-direction
- M_x: Momentum source term in the x-direction
- M_y: Momentum source term in the y-direction
- ν_v: Vertical eddy viscosity
- u: Scalar horizontal velocity component in the x-direction (used in the vertical eddy viscosity term)
- v: Scalar horizontal velocity component in the y-direction (used in the vertical eddy viscosity term)
- ξ: Free surface elevation
- $\overline{U}$: Depth-averaged horizontal velocity component in the x-direction
- $\overline{V}$: Depth-averaged horizontal velocity component in the y-direction
- S: Source or sink term in the continuity equation

B BASIC MODEL INTERFACE

Basic Model Interface (BMI), developed by the Community Surface Dynamics Modeling System, is a component-based environment designed to facilitate the integration of numerical models. The BMI protocol (Peckham et al., 2012) operates by encapsulating models within a 'wrapper,' which acts as a secondary layer for managing simulations enabling coupling of numerical models by coupling inputs and outputs of existing models. This standardizes the process by providing a set of functions for setting up, finalizing and running a model. By implementing BMI, a model gains the capability to interact with other models without changing anything about the models itself. Essentially, BMI serves as a bridge between models, enabling exchange of variables during simulation.

Figure 45 shows the concept of BMI. There are two models with different setups and different ways of running them. If those models are wrapped using BMI, the models now have a standardized interface, depicted as puzzle pieces. Then, the models are standardized and can be coupled, exchanging variables trough BMI.

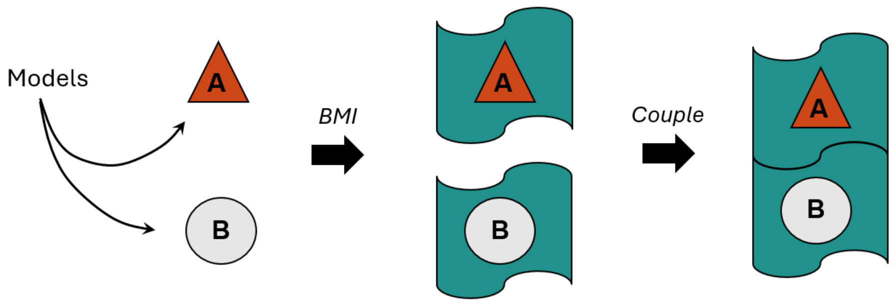


Figure 45: Conceptual depiction of the Basic Model Interface (BMI). Two distinct models, each with their own setups and ways are illustrated. By wrapping them with BMI, represented by the puzzle pieces, these models have a standardized interface. This standardization facilitates coupling between the models.

C DATA-DRIVEN MANIPULATION METHODS

In this thesis, besides the full manipulation method as outlined in this thesis, two other data-driven manipulations were developed and evaluated to manipulate the evolution of shoreface nourishment in Delft3D-FM: the crest-trough method and the slope manipulation method, which focus on selective parts of the nourishment area instead of full manipulation. These methods involve the selection of anchor points (i.e. grid points) across the nourished area, where the bed level is adjusted based on specified parameters. This process includes retrieving the bed level from Delft3D-FM through the BMI, applying the adjustments according to either the crest-trough method or the slope manipulation method, and then feeding the modified bed level back into Delft3D-FM as input for the next timestep.

C.1 THE CREST-TROUGH METHOD

C.1.1 *Description*

The crest-trough method was developed to minimize the amount of anchor points needed to guide the evolution of shoreface nourishments in the hybrid model. This method involves selecting the two most pivotal anchor points (i.e. grid points) per transect over the nourishment, determined on largest amplitudes in the $\Delta z - curve$ of each point (see Figure 50). A $\Delta z - curve$ is a curve that stores the spatial path of an anchor point over the lifetime of the nourishment, based on Jarkus observations. The two points with largest amplitudes in these curves correspond to the anticipated maximum crest height and maximum trough depth that will form during the lifetime of the nourishment. By focusing on only these two anchor points per transect, it limits the required data to their specific evolution, instead of needing information for all anchor points in the nourishment area.

By targeting the two most pivotal points of the nourishment (i.e. crest and trough), this method aimed to steer the nourishment evolution more effectively. Manipulating these two representative anchor points aimed to achieve a better overall representation of the crest and trough's evolution, thereby steering the nourishment in a more efficient and targeted manner.

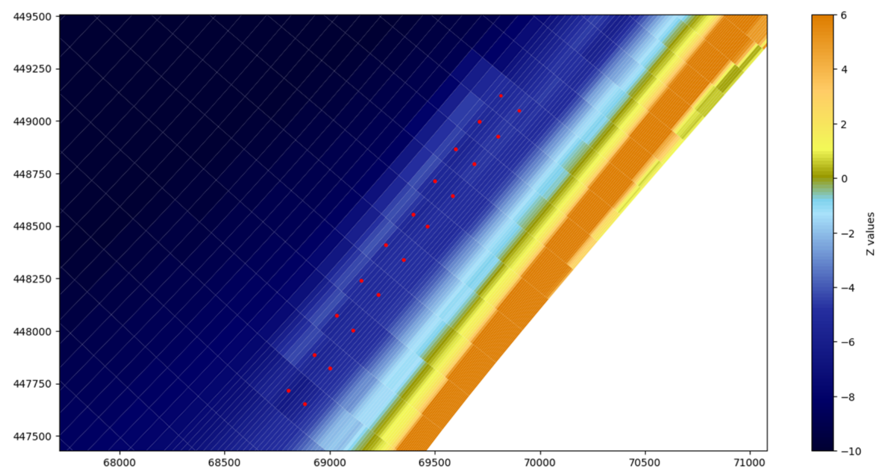


Figure 46: Selected anchor points for the crest-trough method. The method involves selecting two pivotal points to guide shoreface nourishment evolution: the anchor points for the crest and trough. This approach limits data requirements to these pivotal points, and aimed to enhance the ability to predict nourishment evolution.

Additionally, this method aimed to enhance the ability to predict shoreface nourishment evolution. By concentrating on the key points that significantly influence the overall shape and behavior of nourishment evolution, the crest-trough method intended to provide a more manageable framework for forecasting nourishment evolution.

C.1.2 *Results*

The crest-trough method showed poor results, with only the two selected anchor points aligning with the observed nourishment evolution (see Figure 47). The method was based on the hypothesis that the surrounding grid points would follow the manipulated anchor points, but the results do not support this assumption.

A potential explanation for the poor results in the crest-trough method is that altering the bed level only at specific points diverges too greatly from the model's intrinsic behavior. Such manipulation fails to align with the overall sediment transport transport within the model, where the sediment transport field appears to hold dominance (see Chapter 6 for further elaboration).

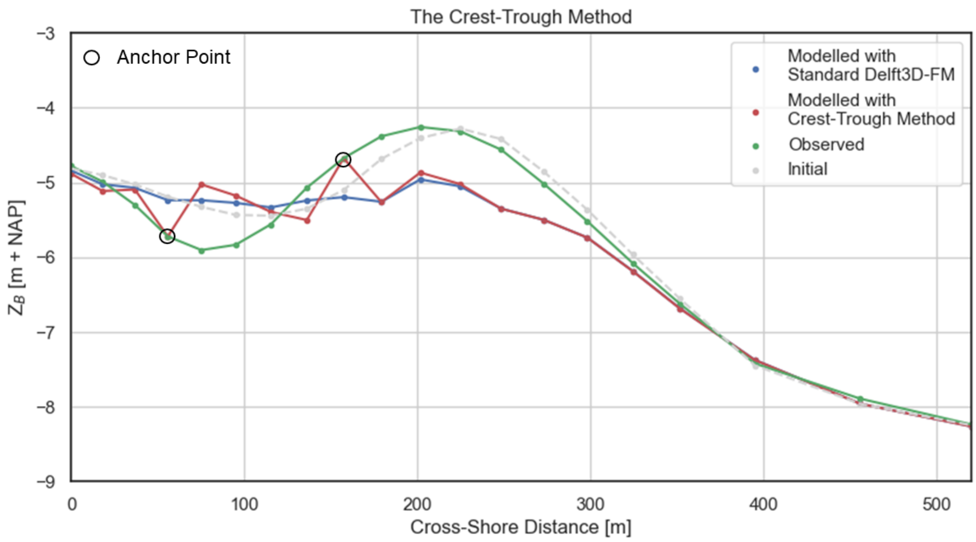


Figure 47: Results of the crest-trough method. The method showed poor results, with only the two selected anchor points aligning with the observed nourishment evolution, and neighbouring grid points not following the desired nourishment evolution.

C.2 SLOPE MANIPULATION METHOD

C.2.1 *Description*

The slope manipulation method focused on manipulating the seaward slope, preventing it from flattening excessively. As the crest-trough method involves two points that are largely overshadowed by wave breaking, manipulating the seaward slope represents a gentler manipulation compared to the crest-trough method, offering the model less margin for error. Instead of manipulating the crest and trough directly, the method aims to preserve the seaward slope, inducing desired evolution landward of this slope to ideally form the desired crest and trough.

Theoretically, it is suggested that the trough follows the evolution of the crest: as the crest increases, the landward slope also increases, thereby prompting the formation of a trough. Therefore, the slope manipulation method is aimed to induce the desired formation of a trough.
In order to see if this method holds potential, the seaward slope of nourishment is held constant by manipulating these anchor points, visualized in Figure 48.

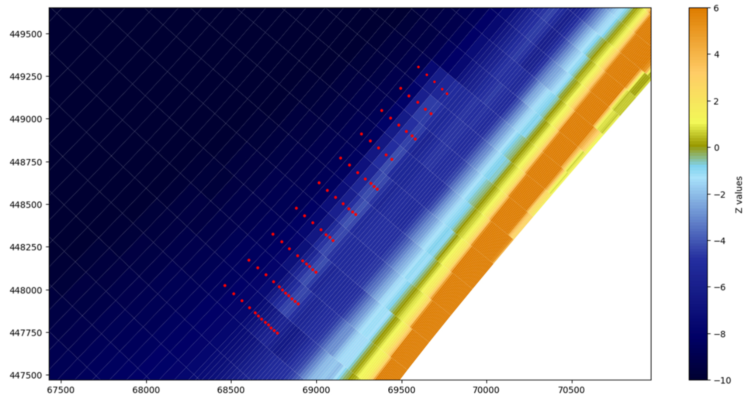


Figure 48: Selected anchor points for the slope manipulation method. The seaward slope is manipulated in such a way that it is held constant.

C.2.2 *Results*

Despite manipulating the seaward slope of the nourishment successfully, the landward evolution of the nourishment is unaffected and similar to the results of the standard model, see Figure 49. This suggests that the slope manipulation method fails to induce the desired landward changes in nourishment evolution. The inability to effectively alter the landward evolution despite modifying the seaward slope outlines the complexity in manipulating in bed level changes. For further discussion on this topic, see Chapter 6.

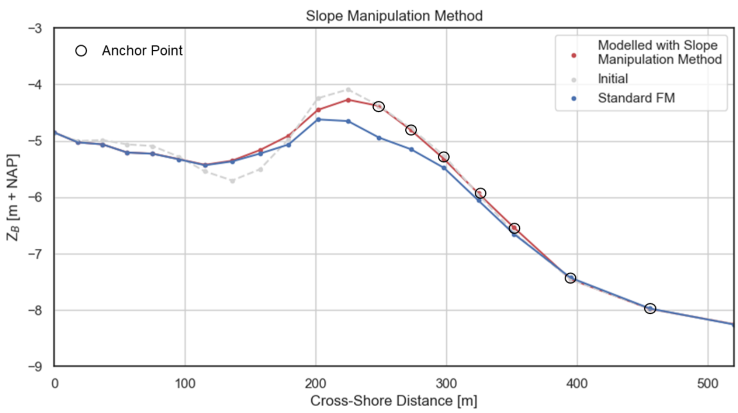


Figure 49: Results of the slope manipulation method. Despite manipulating the seaward slope of the nourishment successfully, the landward evolution of the nourishment is unaffected and similar to the results of the standard model.

C.3 Δz-CURVES FOR CREST-TROUGH METHOD

Figure 50 displays the Δz-curves for a single cross-shore transect. The two outlined plots show the curves for the points with the maximum amplitudes, coinciding with the points with maximum crest height and maximum trough depth during the nourishment's lifetime. These two points serve as the two chosen anchor points used in the crest-trough method.

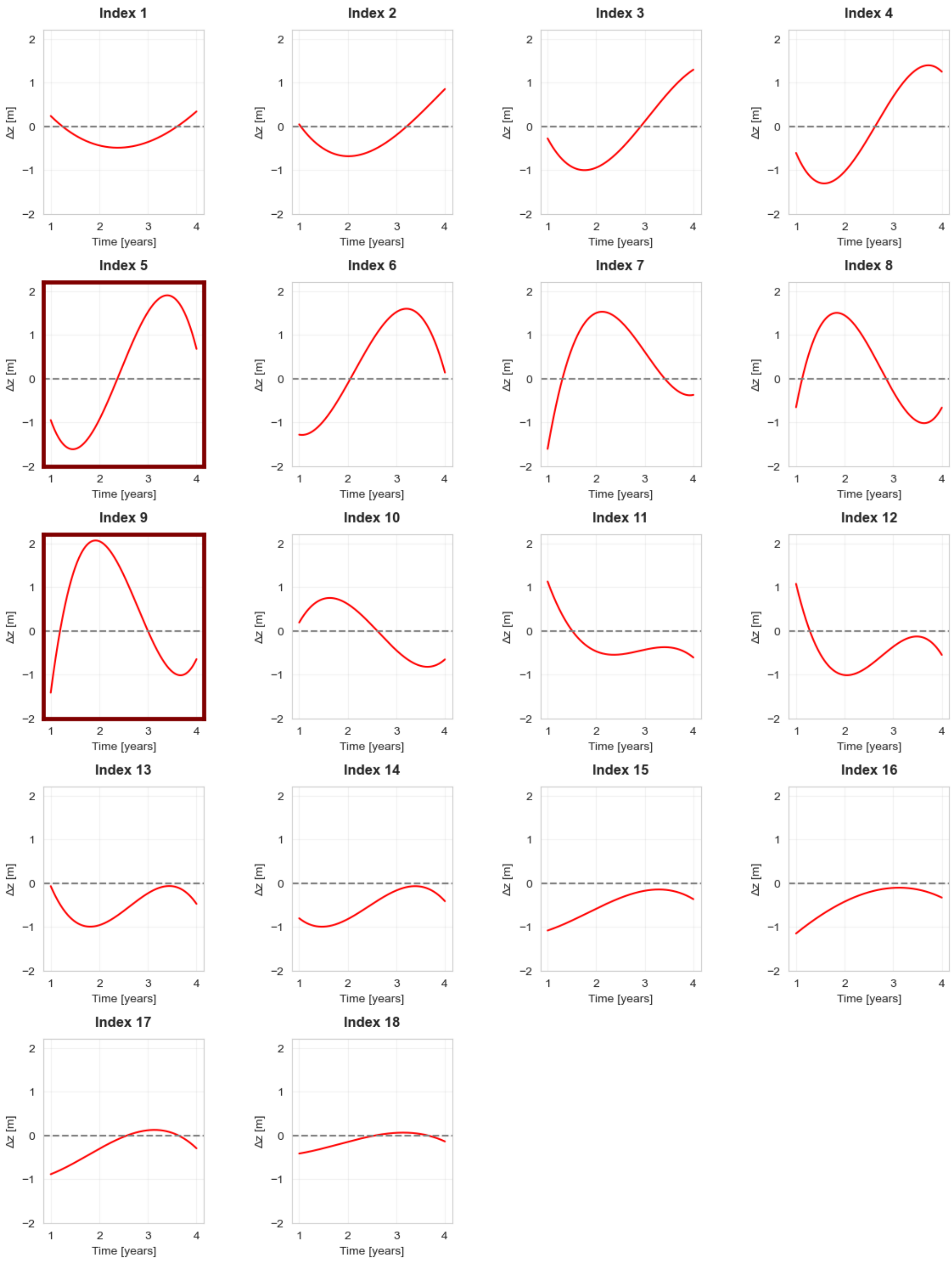


Figure 50: Δz-curves for a single cross-shore transect. The two outlined curves show the curves with the maximum amplitudes, coinciding with the points for with maximum crest height and maximum trough depth during the nourishment's lifetime. These two points form the two pivotal points used in the crest-trough method.

D ADDITIONAL INFORMATION

D.1 COMPUTATIONAL EFFORT

The computational time is given for the model applied at the case study of the Ter Heijde '97 shoreface nourishment, see Figure 51. The computational time divided in the computational time of SWAN, FM and BMI. A significant increase in computational heaviness can be observed, which is dependent on the amount of anchor points used as full manipulation takes more time than the crest-trough method, which only includes two anchor points per transect in stead of twenty for the full manipulation.

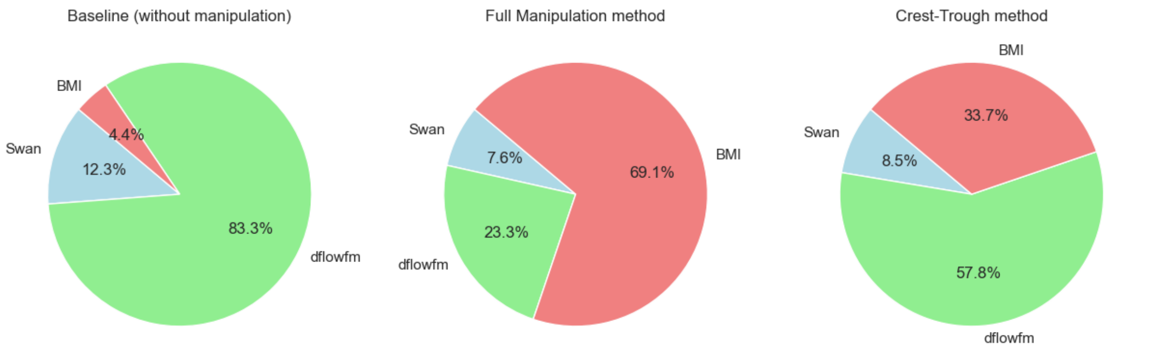


Figure 51: Total computational time of the model. Manipulating using the data-driven component trough Basic Model Interface significantly slows down the simulation. The more anchor points chosen, the slower the simulation.

D.2 OBLIQUE INCIDENT WAVES

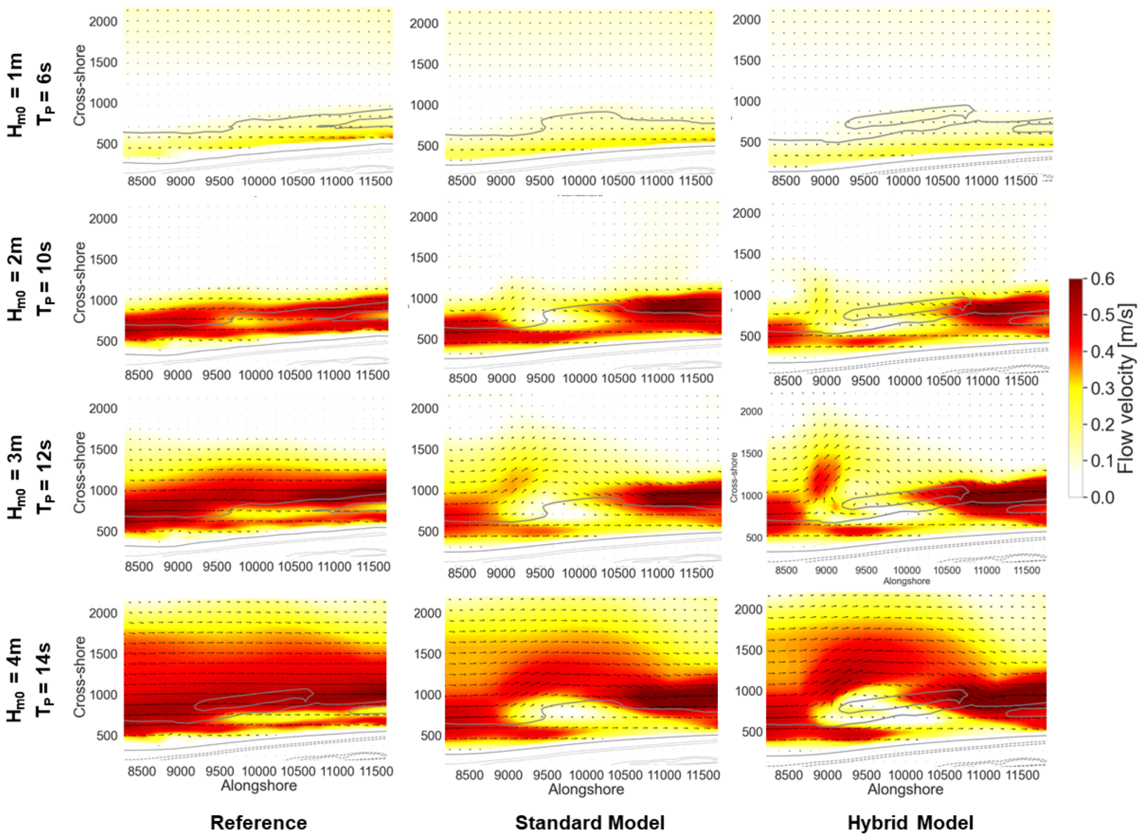


Figure 52: Flow velocities for waves coming from the south-west (285 degrees north, oblique incident waves). Grey contourlines show the bathymetry.

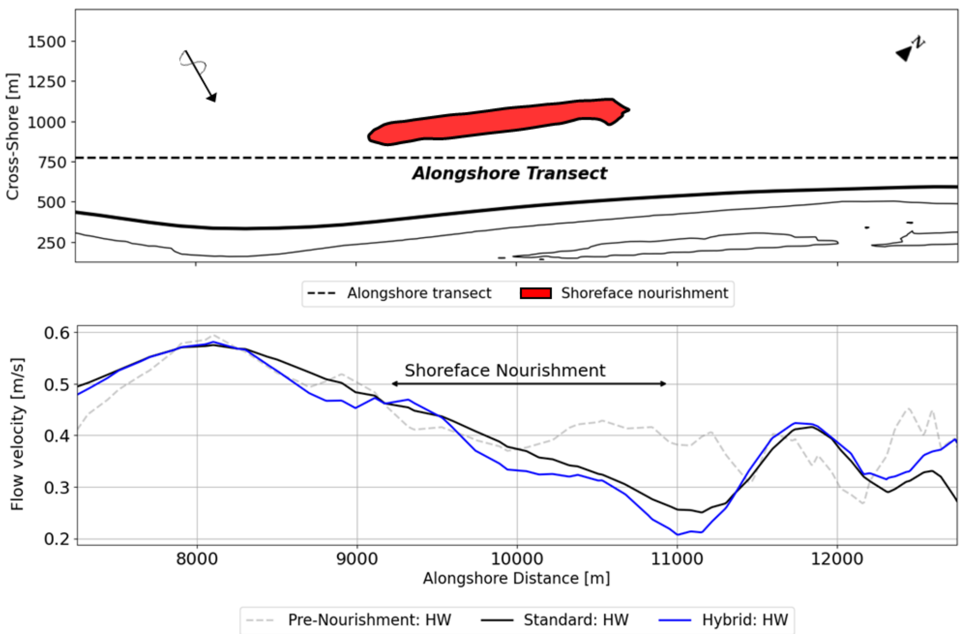


Figure 53: Flow velocity comparison along an alongshore transect under high (HW; H_{m0} = 3m) southwest wave (oblique incident) conditions. The hybrid model shows 20% lower flow velocities in the central point of the lee of the nourishment, indicating a calmer wave climate compared to the standard model.

D.3 THE ANCHOR METHOD

The Anchor Method follows the following procedure for its setup, see Figure 54:

1. Determining the amount and location of the anchor points on the grid. These points are chosen based on the nourishment location.
2. Establishing the vertical yearly displacement Δ_z, derived from measurements at Jarkus transects.
3. Interpolating the Δ_z from Jarkus transects to the exact location of each anchor point and synchronizing them with the timestep used in Delft3D-FM, resulting in a Δ_z-curve, which stores the Δ_z for each timestep in FM.

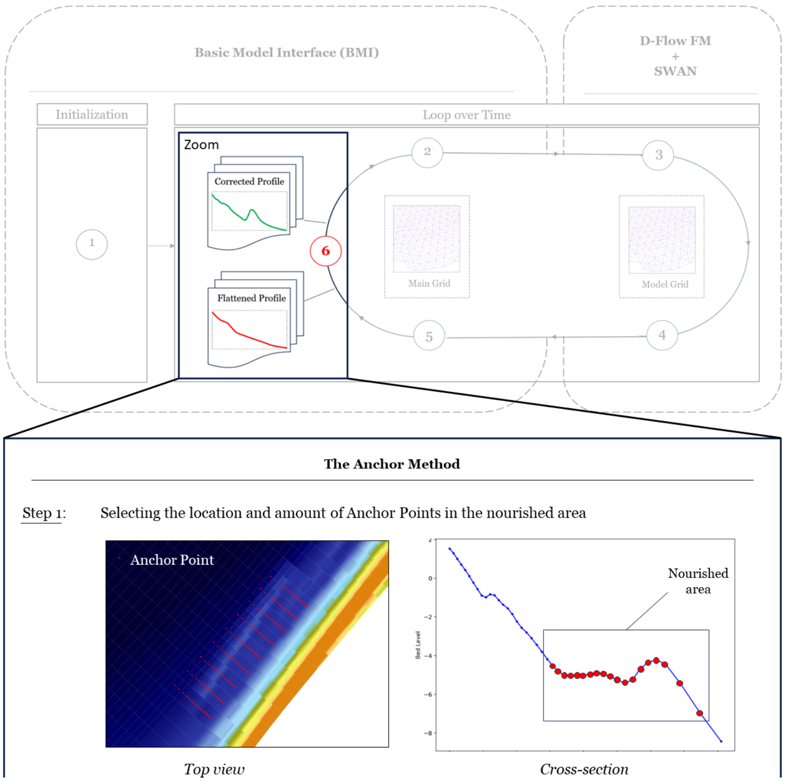
Following these three steps, the simulation will start running, with Delft3D-FM calculations being overwritten by information from the Δ_z-curve for each timestep at each anchor point.

Figure 54 illustrates the anchor method. It shows shows the position of the anchor method within the entire simulation process. For each iteration of the simulation loop, it receives the bed level calculated by Delft3D-FM, which has the tendency to flatten out, corrects it using the anchor method, and then provides the adjusted bed level back into the simulation loop as input for its next timestep.

The zoomed in part of Figure 54 illustrates the steps taken for the implementation of the Anchor Method. Step (1) illustrates the selection for the amount and location of the anchor points, showing the topview and the cross-section. In the nourished area, every grid point is taken as anchor point in this example, totalling 180 anchor points divided over nine cross-shore transects, indicated with red dots.

Step (2) zooms in on one anchor point, and shows the yearly Jarkus measurements and their yearly vertical displacement, Δ_z, stored in a table, for this anchor point.

This data is then interpolated to the exact location of each anchor point in Step (3), synchronized with the timestep used in FM, resulting in the Δ_z-curves for each anchor point.



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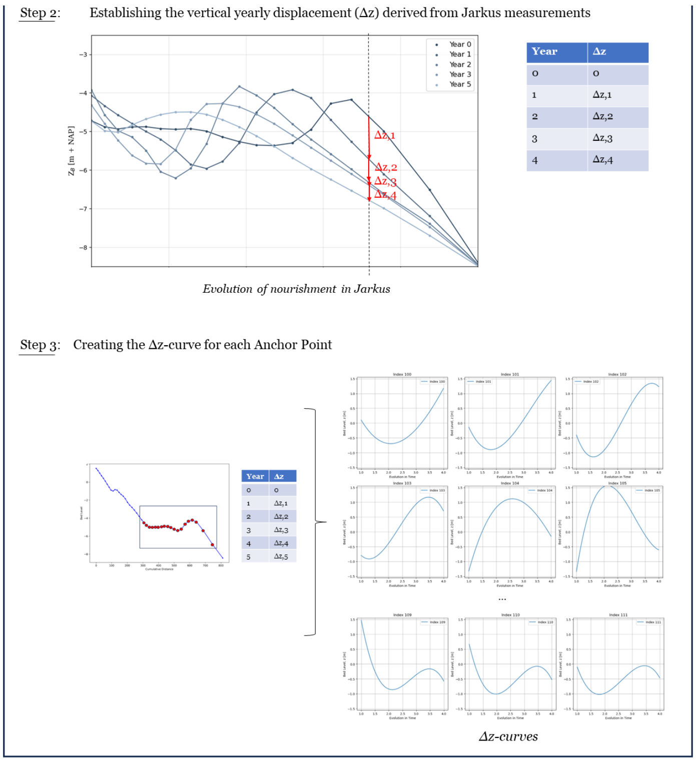

Figure 54: Illustration of the anchor method. The figure depicts position of the Anchor Method within the simulation process, and then zooms in on this process, showing the implementation steps. The steps involve: (1) selecting grid cells as anchor points, determining their quantity and location based on nourishment location, (2) establishing yearly vertical displacement (Δ_z) from Jarkus measurements, and (3) interpolating Δ_z to each anchor point's location. Delft3D-FM receives information from the Δ_z-curve for each timestep at every anchor point during its simulation.

D.4 Δ_z-curves for data-driven manipulation

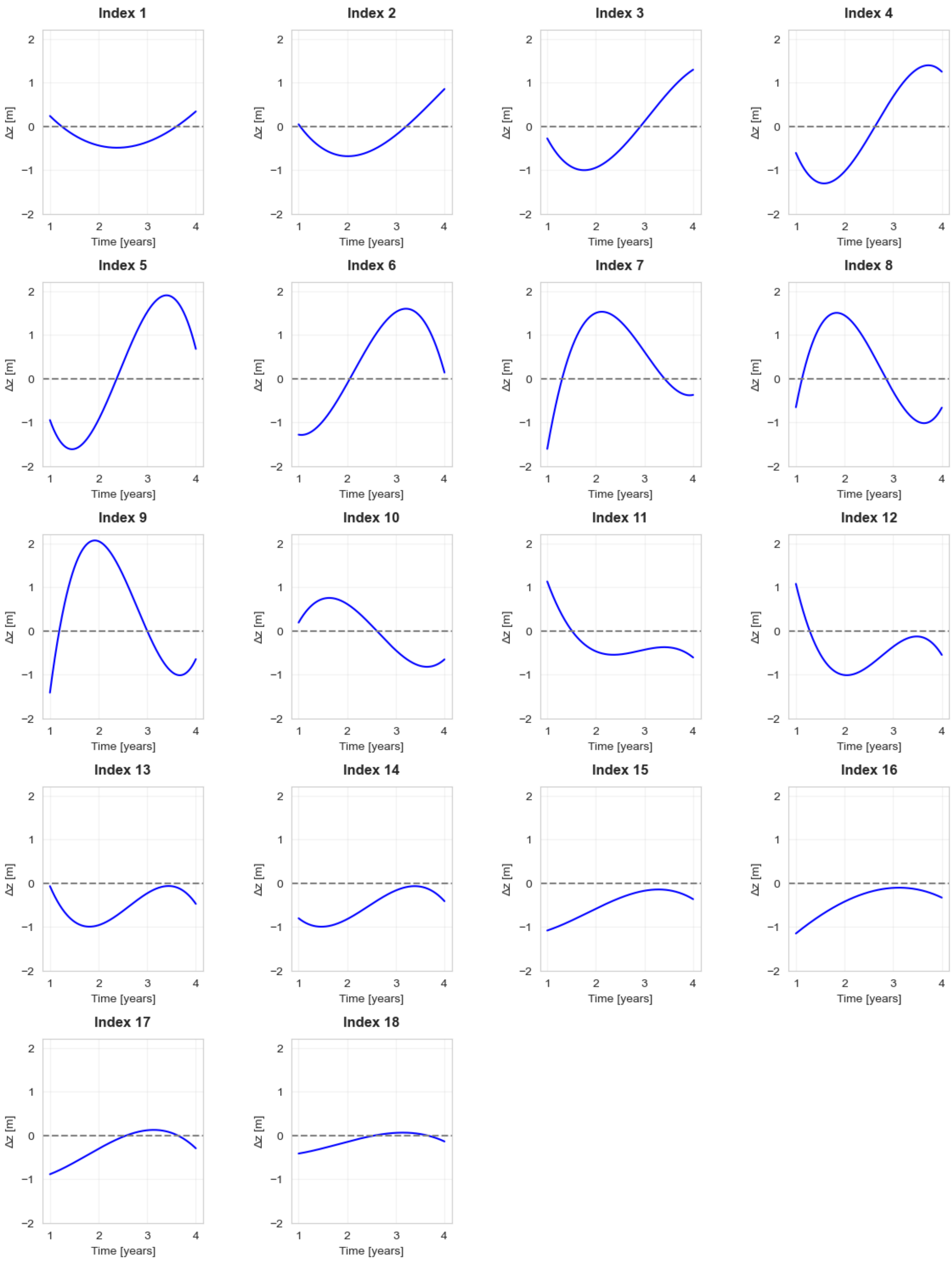

Figure 55: Δ_z-curves for the central transect.

COLOPHON

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